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Cable-driven Parallel Robot to Simulate the Underwater Environment in Humanoids

Ph.D. Thesis

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Resumen

El diseño y control de los robots submarinos tiene que afrontar condiciones submarinas muy distintas a las que se encuentran en tierra. La metodología común para sus pruebas comienza con simulaciones computacionales antes de la inmersión en piscinas reales donde sus algoritmos de control se pueden desarrollar y actualizar con experimentos en el medio acuático. Sin embargo, el salto entre esos dos escenarios de prueba podría ser demasiado amplio para cubrir todos los requisitos del robot que se necesitan en el emplazamiento. Por este motivo, se propone un simulador submarino en tierra basado en tecnología accionada por cable. Este simulador podría crear un escenario donde el robot pueda probar sus algoritmos en un entorno controlado, seguro y personalizable para garantizar la viabilidad de su rendimiento antes de una inmersión real en una piscina.

El trabajo propuesto se centra en incrementar la calidad de la simulación submarina en robots con patas o que puedan tener contacto con el entorno imponiendo al robot las fuerzas de reacción que sentirá sobre el fondo marino real. Además, debido a la configuración multicuerpo que suelen tener esos robots, el robot accionado por cable propuesto pretende manejar esta condición ejerciendo las llaves externas requeridas en más de un cuerpo proporcionando una simulación con mayor calidad al distribuir las fuerzas en diferentes puntos del cuerpo, centrándose en la estructura humanoide. Esta distribución de tensión se puede realizar aprovechando la estructura de restricción redundante del robot accionado por cable atendiendo a las configuraciones de tensión factibles. Esas tensiones podrían proporcionar una amplia gama de energía potencial en los elementos elásticos del efector final donde está conectado el robot submarino. Gestionando esta energía potencial con los actuadores redundantes podría ser posible ejercer las llaves o movimientos deseados en los diferentes cuerpos de un efector final pasivo reconfigurable.

El uso de cables en lugar de eslabones rígidos, así como el esfuerzo de las llaves mediante el uso de mecanismos elásticos y flexibles, permiten la simulación de las condiciones submarinas en sujetos humanos. Esos experimentos específicos, realizados en el RoAR Lab de la Universidad de Columbia, permiten conocer el comportamiento humano en este entorno simulado para ayudar en el desarrollo de algoritmos para robots. Esta nueva aplicación para robots accionados por cable requiere una síntesis, diseño y construcción de un prototipo real capaz de cumplir con los requisitos necesarios. De modo que, se seleccionan diferentes índices de rendimiento y parámetros para definir la forma del robot, así como una selección específica de los componentes. Finalmente, se realizan varios experimentos para validar la simulación submarina atendiendo a la acción de la fuerza de flotabilidad y las fuerzas de reacción deseadas con el suelo.

Abstract

The design and control of underwater robots have to handle with underwater conditions very different from those found on ground. The common methodology for their testing begins with computational simulations before the immersion in real pools where their control algorithms can be developed and upgraded with experiments in the aquatic environment. However, the leap between those two testing scenarios could be too wide to cover all the robot's requirement that are needed in the emplacement. For this reason, an on-ground underwater simulator based on cable-driven technology is proposed. This simulator could create a scenario where the robot can test its algorithms in a controlled, secure and customizable environment to guarantee the feasibility of its performance before a real immersion in a swimming pool.

The proposed work focuses on increase the quality of the underwater simulation on legged robots or those that can have contacts with the surroundings by imposing to the robot the reaction forces that will feel on the real seabed. In addition, due to the multibody configuration that those robots use to have, the proposed cable-driven robot aims to handle with this condition by exerting the required external wrenches in more than one body providing a simulation with higher quality by distributing the forces into different points of the body, focusing on the humanoid structure. This tension distribution can be performed by taking advantage of the redundantly constraint structure of the cable-driven robot attending to the feasible tension configurations. Those tensions could provide a wide range of potential energy on the elastic elements of the end-effector where the underwater robot is attached. Managing this potential energy with the redundant actuators it could be possible to exert desired wrenches or movements in the different bodies of a passive reconfigurable end-effector.

The use of cables instead of rigid links as well as the exertion of the wrenches by using elastic and compliant mechanisms allow the simulation of the underwater conditions into human subjects. Those specific experiments, performed in the RoAR Lab of Columbia University, allow to know about the human behavior in this simulated environment to help in the algorithm development for robots.

This novel application for cable-driven robots requires a synthesis, design and building of a real prototype able to fulfil the requirements needed. So that, different performance indices and parameters are selected to define the shape of the robot as well as a specific selection of the components. Finally, several experiments are performed to validate the underwater simulation attending to the buoyancy force action and the desired reaction forces with the ground, showing that the mechanisms and algorithms implemented to perform a simulation in a articulated underwater robot are suitable for the application.

Acronyms

CDPR: Cable-driven Parallel Robot
EE: End-Effector
SVD: Singular Value Decomposition
WFW: Wrench Feasible Workspace
WCW: Wrench Closure Workspace
ACTDI: All Cable Tension Distribution Index
GTDI: Global Tension Distribution Index
CI: Condition Index
FPB: Feasible Parameter Box
CSIC: Consejo Superior de Investigaciones Científicas
UPM: Universidad Politécnica de Madrid
ETSII: Escuela Técnica Superior de Ingenieros Industriales
RT: Real Time
AWS: Available Wrench Set

Notation

n : Degrees of freedom of the end-effector.
 m : Number of independent actuators.
 r : Degree of redundancy.
 O' : Geometrical center of the end-effector.
 $\{F\}$: Fixed frame.
 $\{M\}$: Mobile frame.
 A_i : Position of last pulleys.
 B_i : Position of the end-effector anchors.
 u_i : Unit vector pointing in the direction of each cable.
 p_i : Vector from O' to B_i
 p_G : Vector from O' to CoM
 l_i : Lengths of cables
 ξ_i : wrench imposed by the cable i to the end-effector.
 τ_i : Cable tension
 F : End-effector force
 M_O : End-effector torque
 J : Jacobian matrix
 A : Wrench or structure Matrix
 N : basis of nullspace
 λ : magnitudes for N
 Λ : Direction of the wrench of the end-effector
 Π_i : Plane corresponding to the tension possibilities.
 l_i : Intersection to Π_i and the limit tension.
 l_i : length of the spring i
 δ : Deformation of the spring
 V_{ij} : intersection between l_i and l_j .
 λ_{opt}^F : nullspace value that provides a maximum wrench.
 Ω : Regions of feasible tension distribution in nullspace
 R_M^F : Rotation matrix for M respect the frame F
 k_i : stiffness

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Contributions

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1.INTRODUCTION

1.1. Cable-driven parallel robots

Cable-Driven Parallel Robots (CDPRs) are parallel mechanisms whose end-effector (EE) is manipulated by using cables that are usually coiled in pulleys and winches attached to a rigid frame. Cables can only exert traction and do not resist compression efforts, so it is necessary to provide opposite forces for each cable to maintain the stiffness. In Fig. 1.1 the main parts of a CDPR are shown: The EE, the winches, the pulleys and the rigid frame. However, some prototypes can be found without one or more of these components like the proposed by (Tobias Bruckmann et al., 2011), substituting the winches by linear guides; the SpiderBot from (A. Capua et al., 2014) which can displace to modify its relation with the external rigid frame or the superball (Vespignani et al., 2018) which has an special distribution of its end-effectors based on tensegrity mechanisms.

Figure 1.1 Main components of a CDPR. A: Winch; B: Cable; C: Rigid Frame; D: Pulleys; E: End-effector.

1.1.1. Advantages of CDPRs

Usually, parallel robots (Jean-Pierre Merlet, 2006) use rigid links, like the Delta robot (Rey & Clavel, 1999) or the Stewart-Gough platform (X.-S. Gao et al., 2005), which can have prismatic or angular actuators in its general form. The use of cables has several advantages mainly due to their high wrench-to-weight ratio and their mechanical simplicity as demonstrated by several prototypes and experiments found in the literature.

One of the main advantages of these CDPR is that they can handle huge workspaces as demonstrated with the Tianyan-FAST radio telescope (Nan et al., 2011), with its 500 meters of diameter, seen in Fig. 1.2A; some mobile aerial camera systems like the SpiderCam (Bai et al., 2019), with its base of 60 x 67 meters used for field research, or the Skycam (Brown, 1985)(J. Bennett et al., 2012), intended for broadcasting sporting events able to cover a football stadium workspace. Other demonstrations of this capability are the NIST SPIDER that has legs of 6 meter length (J. Albus et al., 1992), the Marionet family robots (J. P. Merlet, 2008) that include the Marionet-Crane with 100 x 100 x 50 meters side destined for rescue operations (J.-P. Merlet, 2010)(Jean Pierre Merlet, 2014) or the assembler of solar panels from (Pott et al., 2010) with a plant size of 15 x 8 meters.

This available large workspace has been used in the construction field with examples like the building of concrete (P. Bosscher et al., 2007)(Williams et al., 2008), masonry (T. Bruckmann et al., 2016) or brick (Y. Wu et al., 2018) walls and structures. Even the construction of complex structures are proposed like fusion reactors (J. B. Izard et al., 2015) and special builder robots (Taghavi et al., 2018) base on CDPRs. Their industrial feasibility was analyzed in (Tobias Bruckmann et al., 2017), storage systems were proposed in (Tobias Bruckmann et al., 2013) and also applications like the façade cleaning (Kunst et al., 2005) or airplane inspection robots (Monich et al., 2019).

The low inertia of the cables allows to reach high speeds and accelerations like the FALCON (S. Kawamura et al., 1995) with its 43g of peak acceleration and a maximum velocity of 13m/s shown in Fig. 1.2B;

it was upgraded with the WARP manipulator (Maeda et al., 1999), which increased its accuracy and avoided the disarray of wires. The DeltaBot (Dekker et al., 2006) used a rigid spine connected to the inertial frame to reach accelerations of 8g and peak velocities of 3.9m/s. Redundant configurations have also been considered for reaching high speeds without the need of a rigid spine, as observed in (Aref & Taghirad, 2008).

Figure 1.2 A) The China's Five-hundred-meter Aperture Spherical radio Telescope (FAST) (From chinadaily.com.cn by Dai Chuanfu). B) The Falcon-7, CDP able to reach high speeds and accelerations (From (S. Kawamura et al., 1995)).

This lightweight and low-inertia characteristic from CDPs is widely used for rehabilitation (Tavolieri, 2008) with many research in this field like training of arms as observed in Fig. 1.3A and in (X. Cui et al., 2017)(Mayhew et al., 2005)(Shao et al., 2014)(Zanotto et al., 2014)(Brackbill et al., 2009)(Mao & Agrawal, 2010)(Mao & Agrawal, 2011), hands (Dovat et al., 2008), legs (M. Wu et al., 2011)(Jin et al., 2015) or trunk (M. I. Khan, Prado, et al., 2017)(M. Khan et al., 2019). Also, CDPs are used as assisting devices for elderly people, as proposed in (Castelli & Ottaviano, 2009)(J.-P. Merlet, 2010), for gait training (Vallery et al., 2013) or for people with wheelchair in urban environments as the CaSImo (Cable System for Improving Mobility) (Castelli & Ottaviano, 2014). The properties of the cables can help to accomplish the requirements for flexibility and safety, so this, human-robot collaboration can be developed for their usage as haptic interfaces like (Evreinova et al., 2014)(Ferraresi & Pescarmona, 2010), for sport simulation (Zitzewitz et al., 2009)(von Zitzewitz et al., 2008) like rowing (Rauter et al., 2010), motion simulation (Miermeister et al., 2016), virtual reality as the SPIDAR family (Space Interface Device for Artificial Reality) (Sato, 2002), walking simulation (Otis et al., 2008) and even simulate tactile sensations (Y. Yi & Yuru, 2009). More critical applications were attended like for rescue purposes like the portable CDP shown in (J. P. Merlet & Daney, 2010) and surgery purposes like (Direkwatana et al., 2011)(Yangming Li et al., 2016).

The parallel configuration provides high dexterity (Jean-Pierre Merlet, 2006). The IPAnema family(Pott, Mütterich, Kraus, Schmidt, Miermeister, & Verl, 2013) reached a certified absolute accuracy of less than $10\mu\text{m}$. The ReelAx family (J. B. Izard et al., 2013), whose version CoGiRo is observed in Fig. 1.4A and the CoGiRo-Pylos (J. Izard et al., 2017), which is able to print with material wire of 3mm in thickness. The KNTU (Aref, Taghirad, et al., 2009) was designed attending to increase its dexterous performance. The Cablecrane from Fig. 1.4B combines a high accuracy with a high nominal payload of 3000Kg (Culla et al., 2017). The accuracy can be increased with an adequate model of the cable like the dynamic model of one degree of freedom device from (Yangming Li et al., 2016). The WiRo (Ferraresi et al., 2004)(Wire Robot) uses 9 cables to significantly increase its dexterity along a bigger workspace in comparison with prototypes that have just 7 cables.

Figure 1.3 A) Cable-driven Arm Exoskeleton (CAREX) (From [26]). B) CDPR using the low footprint to move plane models in a wind tunnel (From (X. Liu et al., 2012))

The substitution of rigid links by cables make these robots easier to assemble. This mechanical simplicity also reduces their need for maintenance because the reduced number of mechanical joints that have to handle high efforts like in the case of heavy pistons and cylinders. In (Tadokoro et al., 1999)(P. Bosscher et al., 2005), a portable CDPR is proposed able to be installed in unstructured environments for rescue purposes while in (Campbell et al., 1995) space applications are developed attending to CDPR mechanical simplicity.

The small aerodynamic footprint of the cables allows to propose wire robots for moving ship or planes models in wind tunnels as proposed in (Lafourcade et al., 2002)(Tobias Bruckmann et al., 2011)(Tobias Bruckmann, Mikelsons, Brandt, Schramm, et al., 2009)(X. Liu et al., 2012) or flying cranes underneath airships for carrying goods (Abdallah et al., 2018). Their low hydrodynamic is also suitable for submarine applications like underwater platforms as shown in (Bostelman & Albus, 1993)(Xia et al., 2018) even actuated by ships (Ghaffar & Hassan, 2014) or robots for seabed works like (El-Ghazaly et al., 2015b) or the algae harvester seen in (Noah J. Needler, 2013).

A CDPR doesn't have to be always attached to a rigid structure. Several examples of locomotion have been developed like the suspended SpiderBot (Alon Capua et al., 2010) observed in Fig. 1.5A or the tensegrity structures from (Kim et al., 2020) and its improved version able to absorb large impacts (Vespignani et al., 2018), seen in Fig. 1.5B.

Figure 1.4 A) CoGiRo (From (J. Izard et al., 2017)). B) Cablecrane (From (Culla et al., 2017))

1.1.2. History of CDPRs

The first analysis of a cable-controlled parallel link manipulator was developed in 1984 with the Thesis (Landsberger, 1984), while the first CDPR prototype, the NIST RoboCrane, appeared in 1989 (B. L. Wang et al., 1989)(J. Albus et al., 1992), patented in the same year (J. S. Albus, 1989). The kinetostatics of this type of robots was already proposed in 1988 by Tanaka (Tanaka et al., 1988). In the same year, Higuchi proposed their use for construction (Higuchi, 1988). Haptic interfaces were proposed in 1993 in (Sadao Kawamura & Ito, 1993) and improved with the SPIDAR prototype in (Ishii & Sato, 1994). With the FALCON (S. Kawamura et al., 1995), Kawamura et Al. began using CDPRs with a rigid spine to improve the torque applied and acceleration values. The BetaBot and the DishBot (Behzadipour & Khajepour, 2006) were cable-based manipulators with translational motion aided with the support of this spine by linking the end-effector and the fixed frame. This spine evolved to active supports like (Zhao et al., 2017) able to modify the platform stiffness and dynamics. However, this spine imposes workspace limitations so several CDPR prototypes rejected its use like the Segesta project (Verhoeven, 2004)(Hiller et al., 2005) in 2004 whose objective was the analysis of the kinematics and to improve the control algorithms and the mechanical design, having the capacity to reach accelerations of 200m/s^2 . In the same year, the String-Man, the first CDPR applied for rehabilitation was developed (D. Surdilovic & Bernhardt, 2004). Those application of the CDPR as human-machine collaborative platforms began with the NASA's teleoperator system Texas 9-String Kinesthetic Joystick in 1989 (Lindemann & Tesar, 1989). This teleoperation system was benefited by the higher stiffness and reduced backlash of cable-driven systems was already observed in 1988 (Salisbury et al., 1988). An improved teleoperation system with radial distribution of cables is presented in (Sadao Kawamura & Ito, 1993), where an improved tension distribution algorithm was applied. The implementation of this kind of robot require previous simulations and optimizations as done in (Kraft & Schäper, 2005) or the hardware-in-the-loop simulation proposed in (Diao, 2007). In 2016, the first open-source platform appeared for simulating CDPRs (Lau et al., 2016) expanding the research possibilities of these robots.

Figure 1.5 *A) SpiderBot, a CDPR prototype able to disconnect the cables from the ceiling and reconnect them to displace the platform (From (Alon Capua et al., 2010)). B) The Superball V2 (From (Vespignani et al., 2018))*

1.1.3. Classification of CDPR

A common used classification for CDPR is based on their EE's DoF (n) and the number of actuated cables (m), according to (Ming & Higuchi, 1994). Other classification of those mechanisms can be according to their topology: parallel, serial, hybrid or differential, as defined in (Hong et al., 2018).

According to the capability of the cables to maintain the end-effector position, the CDPRs are classified in under-constrained or “incompletely restrained positioning mechanisms” (IRPM), which need additional external forces for stabilization and fully-constrained or “completely restrained positioning mechanisms” (CRPM), which have, at least one cable more than the degrees of freedom of the end-effector (Ming & Higuchi, 1994).

In (Lakshiminarayana, 1978), it was demonstrated that a rigid body with n degrees of freedom can be completely constrained by $n + 1$ point contacts. This theorem was applied to cable-driven systems in (Kurtz & Hayward, 1991). In (Verhoeven, 2004), the “redundantly restrained positioning mechanisms” (RRPM) are defined as those with at least two more cables than degrees of freedom. The additional cable is needed to fulfil the requirement that all cables have to be under traction effort. This property of maintaining all cables under tension was defined as “tensionability” in (Landsberger, 1992).

In the case of CDPR with suspended configuration (J. L. Pusey, 2006)(J. Pusey et al., 2004), the gravity force acts as a virtual cable to maintain the cables in tension. The static equilibrium of this configuration is studied in (Roberts et al., 1998) based on the null-space characteristics and a local definition of a kinematic fully constrained configuration is provided while its stability is analyzed in (Park et al., 2005). As explained in (Lamaury et al., 2012), tension distribution is important in this kind of under-constrained robot. Suspended configuration also uses to require high loaded platforms to increase the valid tension range in each cable. However, some applications can be developed where the gravity is not the force that maintain the cable tension but the buoyancy as seen in (C. Lambert et al., 2007), where an helium-filled aerostat provides a constant upward force to the end effector. Also in (Xia et al., 2018)(Horoub et al., 2018) this additional force is exerted by the water in a submerged platform.

The selection of the cable and its material has a high impact in the behavior of the robot. Several types of materials are used and studied in literature. In (Freire et al., 2006), steel cables are analyzed attending to their geometric nonlinear effects and their relevance of the sag effect. In (Austin et al., 2015), nonlinear rubber springs were used because they present high stiffness and force resolution. The kinematics of CDPR with plastic fiber ropes were studied in detail in (Weis et al., 2013)(V. L. Schmidt, 2017). In (Abbasnejad & Ren, 2017), each link was composed by several hunches of elastic steel wires. Other types of cables used in industry, like the carbon fiber reinforced polymers (CFRP) (Xie et al., 2014) are not observed yet in prototypes. To avoid heavy and complex actuators or straight cables, Bowden cables, which are high-friction transmission systems were implemented to transmit efforts to different parts like in the case of the human body as developed in (Veneman et al., 2006)(Pont et al., 2019). Despite the material of the cable, different methods of acting them were used: Modifying the cable length by coiling the cable around a winch as in (Pott, Mütterich, Kraus, Schmidt, Miermeister, & Verl, 2013) or using linear actuators as in (J. P. Merlet, 2008), moving cables with constant length along a guide as in (Tobias Bruckmann et al., 2011) or twisting the cables to achieve high positional resolution as in (Shoham, 2005).

1.1.4. Stiffness and stability

Different mathematic models are developed for the cables: From the models that considers the linear deformation like in (Jean-Pierre Merlet, 2009a) to those models that also consider the catenary shape and the inner elongation like those presented in (Nguyen et al., 2013)(Marc Gouttefarde et al., 2012)(Nguyen et al., 2013). In (Su et al., 2001)(Kozak et al., 2006), both models are compared observing that despite the sagging cables can alter the kinematics analysis, this error can be reduced for those cases where a heavy loaded end-effector is used and a straight elastic model is used. In (Nguyen, 2014) the coiling model around the winches and thermal effects are also included. Dynamic analyses of the cable are performed in (Yuan, 2015) to develop stiffness models. In (Du & Agrawal, 2015), a distributed mass model is performed to attenuate the vibration effect of long cables. An hysteresis model is developed in (Miyasaka et al., 2016). Internal damping of steel cables is analyzed in (Qiu, 2013). In (Otis et al., 2009), the position error due to the sagging effect is analyzed observing that this error can be neglected.

One cable can only handle forces along its axis, so that, the stiffness of the end-effector required a deep analysis as performed in (Lafourcade et al., 2004) and (Behzadipour & Khajepour, 2005), where the conditions of stability were analyzed considering stiffness and internal forces in the cables of CDPR. The stiffness of a CDPR is compound by the structural wire stiffness and geometric stiffness (Dragoljub Surdilovic et al., 2013). Different cable routing configurations were analyzed in (Williams et al., 2008) to increase the stiffness of a CDPR with 12 cables. The stability conditions under external disturbances were studied for under constrained CDPR in (P. M. Bosscher, 2004). Motion control of the fully constrained type can be found in (Ghasemi et al., 2009).

The control of elastic parallel robots was studied in (M. a Khosravi et al., 2014). In (Baklouti et al., 2019), a compensator of cable elasticity is proposed, while the main uncertainties due to the elasto-geometric model are listed in (Baklouti et al., 2018). Force control is deeply studied for elastic cables in (Kraus, 2016). An elastic model is related to the appearance of vibrations, as seen in (Diao & Ma, 2009), which also requires a method for handling vibrations, as seen in the adaptive method from (H. Jamshidifar et al., 2015) or the active vibration in modal space proposed in (X. Weber et al., 2015), the robust PID as in (M. A. Khosravi & Taghirad, 2013), or mechanical elements, like reaction wheels (X. Weber et al., 2014). This consideration and handling of the vibration phenomena can be seen in relevant prototypes like FAST (Z. Liu et al., 2013) or Cogiro (El-Ghazaly et al., 2015a).

Due to the correspondence between the direction of the cable and its force exerted to the end-effector, in order to provide a desired wrench when the platform is situated and oriented in some regions, the cables could interfere with each other. In (Blanchet & Merlet, 2014) and (Carpio-Alemán et al., 2018), this cable collision is analyzed while in (Otis et al., 2009), the Interference Estimated Time of Arrival (IETA) is calculated to prepare the tension distribution algorithm to release the tension from the cable that is going to fail.

1.2. Motivation

This research began attending to the problems and difficulties detected while performing experiments with underwater robots in aquatic environments in the Centre for Automation and Robotics (R Saltaren & Rossi, 2017). Specifically, the underwater transformable anthropoid robot “DiverBot” (Ejarque Rinaldini, 2014) (Roque Saltaren et al., 2018) seen in Fig. 1.6. In that research, a 183Kg humanoid articulated robot with 23 DoF, was designed for underwater walking, crawling, navigation with a ROV configuration and manual tasks by using teleoperation from ground. Those experiments were performed mainly in a pool where the robot performed the programed actions.

Figure 1.6 *DiverBot, the underwater transformable anthropoid robot. A) Scheme of components. B) Walking and navigation experiments. C) Telemanipulation and grasping experiments.*

Working in an aquatic environment presents a series of inconveniences that have to be considered before the experiment stage:

1. The physical properties of the ground inside the pools where the robot learns use to be slippery, which difficult the crawling control algorithms because they use to depend on the friction between the floor and the limbs.
2. Dimensions of practice pools use to be too small so the robot motion is constrained to that region.
3. If the tests are developed in oceans, lakes or rivers, the terrain is uneven and has obstacles like rocks, algae or rifts that require an additional control for the robot to consider and handle them. Basic control algorithms developed at first stages would find difficulties to achieve their objectives in those real environments.
4. The inherent characteristics of the aquatic environment present some additional difficulties that has to be considered like the underwater currents, turbidity or the viscosity.
5. When the robot is submerged, the most common sources of failure are related with water infiltration or hydraulic oil leaks. Those failures could produce high damage to the electronics of the robot and the surrounding environment.
6. The access to the robot is more difficult while performing the experiments by technicians that would require to make in-situ repairs, modifications of the robot's mechanisms or making brief tests or measurements. Swimming suits and autonomous breathing devices should be needed to access to the emplacement of the robot during the tasks.

Attending to the advantages of the CDPs related with their big workspaces, high wrench-to-weight ratio and low inertia, the underwater dynamics and conditions are intended to be replied by using this kind of robot. In this way, the CDP could serve as a testbed for training underwater robots before testing them in the aquatic environment and after computer simulations of their control algorithms. The feasibility of the CDPs was already demonstrated in previous works based on exerting controlled forces to humans for rehabilitation like the string-man (D. Surdilovic & Bernhardt, 2004)(Mao et al., 2015) or haptic interfaces for locomotion like in (Ghasemi et al., 2009) (Zitzewitz et al., 2009) or the works developed in (Martelli et al., 2017)(Jin et al., 2015) to improve the gait.

Considering haptic applications, the substitution of rigid links towards cables can improve the transparency of the robot due to the lower inertia exerted to the human, reducing the interaction of the robot when

it is not needed. These dynamics effects can also be reduced in other mechanisms with high mass by using algorithms for gravity compensation (Kelly, 2006) or by using passive elastic compensation, which produces lower interaction forces with the user as observed in (Vallery et al., 2009), when performing motions approximately known in advance, like gaiting or crawling. Admittance control is used in (Ho et al., 2015) to control for different stiffness states. In (Hu et al., 2010), a method for increasing the resolution of haptic CDPR is proposed, reaching translational resolutions below 0.05mm and rotational resolutions below 0.06°, being the encoder the most restrictive element for achieving better results and not the cables.

Body weight supports (BWS) usually consist on a single cable pulling upwards the subject. However, the use of one single cable to reduce or release the gravity force acting on the subject requires the cable to be always vertical during his translation. In (Hidler et al., 2011), the “ZeroG prototype” for gait training allows the winch to be moved along a rail over the subject to preserve this verticality, however this solution restricts the path that the subject can follow to that linear guide. In (Valle, 2017), gimbal mechanisms are used to maintain the force exerted by a single cable to the subject vertical, however, the high mass of those devices restrict the dynamic movement and reduce their bandwidth. In addition, by using just one vertical cable it is not possible to handle side loads or moments (B. L. Wang et al., 1989), that are necessary for an appropriate simulation of underwater forces.

The proposed simulator aims to simulate forces like buoyancy, water drag forces or submarine currents on underwater humanoid robots. This research, however, offers a wide range of applications due to the advantages of the CDPR. One of them could be to find some applications in humans that could be interesting to explore as well as to learn about innate behavior and movements of humans when using the underwater simulator to improve the control algorithms of the underwater humanoid robots. Other fields of research that the proposed simulator offers are related with the simulations of different dynamics like collisions, the space dynamics or special conditions to train specific behavior of the robots. Other part of the research could be focused on the anchor points of the cables in the humanoid to exert the wrenches in the appropriate regions of the body to generate an adequate simulation in the whole body, considering the rigid limbs of the robots and also the more delicate mechanics of the human body.

1.3. Objectives

The main objective of this work is to design, build and control a CDPR able to simulate the underwater conditions on ground aiming to apply it to underwater robots that will use it as a testbed to improve their walking control algorithms. The initial specifications that the CDPR have to fulfil were defined attending to the requirements and performance of the previously developed underwater humanoid robot “DiverBot” shown in Fig. 1.6.

Due to the novelty of this application, a secondary objective is to define parameters, conditions or devices that could increase the quality of the underwater simulation of a humanoid robot. This objective includes the analysis of different measures that could be used to validate or quantify the quality of the underwater simulation performance.

The specific objectives are:

1. Perform a high-quality underwater simulation in a region of at least 3 x 3-meter base and 2.5-meter height.

The base area is defined attending to the space needed by the humanoid robot to perform basic movements, calibrations and algorithm developing while it is not displacing. This high-quality region should be used to perform accurate calibrations in the humanoid or perform experiments that require accuracy in the aquatic environment and not necessarily displacements like manipulating, changing the body balance, jumping, or move the limbs while standing on two legs. The maximum height is selected due to the size of the humanoid robot that is approximately 2 meters when it is stand on feet and 0.8 meters approximately when it is transformed into the ROV mode.

2. Allow a maximum linear speed of the humanoid of at least 1.5 m/s in every direction.

This speed has been chosen attending to studies about velocity of walking in common environments, like the performed in (Martín Bermejo, 2007).

3. Have a workspace as wide as possible.

The workspace will be the region where the robot will displace under the simulation. The size of this volume is independent of the quality of the simulation searched in the reduced region defined in the first specific objective.

4. Having the capacity to handle a mass of 150Kg.

Despite the weight of DiverBot is 180Kg, the second version of this robot is aimed to have a reduced mass lower than 150Kg. It is needed to consider also the dynamic effects that can increase this load.

1.4. Methodology

Due to the existence of fixed objectives to reach and a CDPR that will serve as a testbed for underwater robots, it is useful to follow an engineering methodology that could guide the works towards the final solution expected. However, due to the novelty of the application some objectives are not totally clear at first stages because the literature couldn't provide the required answers to advance with the developments or to understand the feasibility of some procedures, mechanisms, control algorithms or the appropriate response of the system. This uncertain in the path to follow to achieve some objectives as well as the unknown response of the system to specific inputs establish some research questions that would require a scientific methodology to handle appropriately. This scientific methodology would serve in this work as a tool to help to achieve the final objectives set by testing novel experiments able to develop and understand the feasibility of the solutions proposed to meet the objectives.

1.4.1. Engineering methodology

The objectives define the goal needed to achieve. The steps towards a final prototype able to perform the desired tasks and fulfil the desired requirements follow the engineering method defined in Fig. 1.7. The problem definition was born from the need of a testing platform able to simulate underwater robots on ground to avoid the problems associate to a premature test in aquatic environments. The engineering background research is focused on different existing solutions able to solve the aquatic environment difficulties.

Some related solutions previously considered were the multibody dynamics software simulations like in (Manhães et al., 2016). Those software simulations could exert the aquatic associate wrenches to the underwater robot models to help in the development of control algorithms. Some design methodology is based on this type of co-simulation processes, like in (Bruno et al., 2007). However, these simulations have several drawbacks:

1. A costly CAD design process is needed to define all those relevant parts, some of them from commercial catalogs, and to impose their corresponding restrictions and degrees of freedom in the complete assembly of the robot.
2. The dynamic model of the robot needs to be recreated in the virtual simulator. Some of those dynamic features are difficult and costly to obtain and require lot of time to be measured. This would increase the cost of simulations of each robot model. Some of those dynamic parameters are the friction and viscous effects, limb center of mass, motors and actuators dynamic response or processors and data acquisition systems (DAQ) performance. The contact forces between the robot and the ground or the environment are also difficult to model due to the high dependence between the material stiffness.
3. The leap between software underwater simulation and real aquatic environment could be too wide and difficult to handle due to the big number of variables and source of problems that can appear, as explained in the section 1.2.

Other related solutions for the problem could be rigid link robots to support the weight of the underwater robot, spring systems like in (Agrawal & Agrawal, 2005), crane-like devices as in (Valle, 2017) or even make tests in microgravity with parabolic flights (Patron et al., 2005) or in outer space (B. Weber et al., 2017) due to the similarities of this environment with the underwater environment. Attending to the advantages and specific benefits that CDPR could provide to the underwater simulation, already defined in the section 1.1, this system was chosen as the initial solution to develop for this problem.

The selection of the initial requirements is based on the maximum performance expected in the current versions of articulated underwater robots in the Group of Robotics and Intelligent Machines from the Center of Automation and Robotics (CAR).

The following steps of the engineering methodology are based on iterative develop of prototype solutions and tests to validate if they meet the requirements. When results are not achieved, modifications and upgrades are performed on the weaker subsystems from the design to the control algorithms. Inside this iterative loop of developing and testing, a scientific methodology is included. This inner methodology begins with research questions that are near to the border of knowledge to design more effective solutions for the main problem, to perform deeper analysis of this novel kind of robot simulator and also propose new questions related with this field.

1.4.2. Scientific methodology

The research questions that initiate the scientific method are proposed in the first stages of the prototype design, inside the engineering methodology, as seen in Fig. 1.7. New research questions also appear in the last stages after analyzing the results and validating the hypothesis in the discussion stage.

The literature research under the use of this methodology is more focused to provide answers to the research questions, possible paths to face it and a base to construct the hypotheses. Those hypotheses are initial and unproven explanations based on the state of the art and the intuition and are the basis for the experiments.

Those experiments are designed to focus on the hypothesis's assumption and with enough data to provide an adequate discussion in case of they are aligned or not with the hypotheses.

Results obtained from the experiments provide evidences of the real behavior of the system. In those cases where the hypotheses can be validated due to the data, better solutions of the initial engineering problem can be developed attending to this new knowledge. In addition, those data can lead to new questions that need to be evaluated according to the project needs. The set of linked research questions with their discussions and experiments, which provide a knowledge useful for the solution of the engineering problem proposed, lead to this thesis.

Figure 1.1.7.- Scheme of the methodology followed in this thesis combining the engineering method to reach the objectives and the scientific method to increase the knowledge and propose novel solutions after the hypothesis validation.

1.5. Research Questions

The quest for increased quality of the underwater simulation defines some research question towards the analysis of the anchor points in the humanoid that works as an end-effector. The analysis of novel mechanisms and algorithms to spread the forces of the cables along the body is required to avoid damaging some parts due to the excessive pressure imposed in just few points. Attending to the freedom that the subject has while performing the simulation, the elastic energy stored in the cables could be useful to relate it with the movements. Due to the research on humanoid robots, a good idea seems to be the analysis of humans under the conditions of the underwater simulation to test its performance and to learn about the human body's synergies when performing tasks in the simulated submarine environment.

Those research questions, that are the base of the hypothesis could be concentrated in the following way:

1. How could the redundant constraint of a CDPR improve the quality of the simulation of the aquatic environment applied to underwater robots?
2. What are the dimensions and shape of the CDPR to guaranty a high-quality underwater simulation?
3. Is the innate behavior of the human body similar in an underwater simulator based on CDPR and in the aquatic environment?

1.6. Summary

Chapter 1 has established the basic definitions and advantages of the CDPR and why they could help to solve the proposed problem. This problem has been defined and also the methodology to use combining the engineering with the scientific method. The initial research questions have been asked, being the initial point to develop this thesis.

Chapter 2 begins to analyze the redundant configuration of the CDPR to handle the first research question. The nullspace of the structure matrix is used, after other methods, to control the redundancy. The limitations of the CDPR are analyzed to discuss the feasibility of a CDPR to fulfil the objectives, like the maximum wrenches allowed or the speed of the redundancy control. A novel fast tension planner is developed to accelerate the movement in the nullspace with security and also an analysis of the maximum wrenches on the end-effector is performed when the cable tensions are not limited.

Chapter 3 takes the knowledge acquired in chapter 2 to convert the control of the nullspace into additional movements of the end-effector. A novel mechanism is developed and patented able to use the actuation redundancy to control the end-effector as a mechanism of 1 DoF. The experiments were performed with the small prototype “CARCinos”.

Chapter 4 unifies the additional movements developed in chapter 3 and the tensions into energetic magnitudes. The energy stored in the cables is analyzed allowing to control wrenches or movements in an articulated end-effector. When the end-effector is substituted by a humanoid, those controlled energies in different parts of the body will increase the quality of the simulation. One secondary application developed was a gripper able to be used in harsh environments because it doesn't have any electronic device in the end-effector.

Chapter 5 addressed the second research question and calculate the dimensions and shape of a CDPR able to guaranty a high-quality simulation based on indices that maximize the feasible nullspace region, minimize the secure tensions (defined as those farthest from failure) and maximize a condition index defined with physical meaning.

Chapter 6 is a summary of the design and building process of the CDPR, that took the most of time of this work. This chapter defines the engineering processes in the selection of motors, electric material, electronic devices, mechanical components, etc. The design and building of the winches from scratch as well as the structure, conceived with a modularity concept. The end-effector was builded based on the results of the chapters 2, 3 and 4 able to support wrenches in its 6 DoF and also in a secondary body with 1 DoF respect the main body.

Chapter 7 shows the experiments towards the underwater simulation with the CDPR. In this chapter, the experiments were performed with a rigid end-effector, measuring its ground reaction forces to validate the quality of the simulation. In this chapter, the third research question was analyzed thanks to the collaboration with the RoAR Lab from the Columbia University and Prof. Sunil Agrawal.

Chapter 8 expand the underwater simulation of chapter 7 to an articulated end-effector with a secondary body of 1 DoF. This system allows to handle two different bodies of the humanoid to spread the underwater forces and avoid concentrate them in a single point. In addition, underwater currents or collisions can also be simulated in the second body.

Chapter 9 offers a general and final discussion attending to the results of all the experiments.

2. REDUNDANCY RESOLUTION

2.1. Introduction

As defined in chapter 1, redundantly constrained CDPRs are those that have at least two cables more than the degrees of freedom of the end-effector. If m is the number of cables and n the end-effector degrees of freedom, a redundantly constrained CDPR is actuated by $m \geq n + 2$ cables. This means that the degree of redundancy is $r = m - n \geq 2$. These robots are called “redundantly restrained positioning mechanisms” (RRPM). Each limb of those parallel robots has one degree of actuation, so that, kinematic redundancy is not possible because the inverse kinematics (IK) solution is unique (Dasgupta & Mruthyunjaya, 1998). Those type of robots can achieve force redundancy because there are infinite tension configurations for each wrench applied in the end-effector. Hybrid kinematic structures could also achieve kinematic redundancy (Thomas et al., 2002).

In RRPM, the static cable tension use to be undefined for a certain wrench applied in the end-effector. This fact allows infinite solutions for the tension distribution in the cables, just limited by the maximum and minimum allowed tension. In this way, the workspace where the desired wrench can be applied to the end-effector is increased due to the higher possibilities to apply it. In the same way, it is more difficult to be affected by singular configurations. Another additional advantage of actuator redundancy is the possibility to use the additional sources of controlled power to exert secondary tasks to the end-effector (Baerlocher & Boulic, 1998).

This redundant configuration is commonly used in CDPR to compensate their unilateral constraint produced by their incapability to push a cable without bend. This problem is similar to the multi-fingered grasping, as observed in (Ebert-Uphoff & Voglewede, 2004). However, force closure could be achieved without the need of actuator redundancy, as demonstrated with a CDPR with 2 DoF developed in (H. Liu et al., 2014). The objective of this research is to provide realistic underwater simulations, so that, in this chapter 2, the redundant configuration will be used to provide soft and secure tension planners to provide a more fluid experience in the end-effector, even in those cases where maximum wrenches are applied. This actuator redundancy will be also used in chapters 3 and 4 to provide additional movements in the end-effector to distribute the forces of the underwater simulation along the body of the subject.

Having more actuated cables than DoF in the end-effector impose infinite solutions for the tension distribution along the cables to provides a required wrench in the end effector. This tension distribution needs to be handled by using an appropriate algorithm that avoid slackness or over tensions in real-time (RT) and provides an intuitive way to represent the current tension configuration. This graphical and physical related representation of the tension distribution presented in chapter 2, 3 and 4 will help to design and analyze the secondary tasks provided by the actuator redundancy.

After the engineering background research defined in subsection 1.4.1, a suspended CDPR (also known as crane configuration) was selected for this application of underwater simulation, already explained in detail in chapter 1. This kind of configuration normally situates the end-effector below the last pulleys, so that, the cable tension is provided by the gravity force exerted in the platform. This constant vertical force can be modeled as a virtual cable tension pulling down toward the floor. A CDPR with this configuration needs to check if the requirements can be fulfilled and how to handle the actuator redundancy and the tension distribution according to this specification. Those characteristics of suspended CDPR are also analyzed in this chapter.

The virtual cable representing gravity force applies a vertical constant force proportional to the end-effector mass. Cable tension will have an upper boundary due to the restriction imposed by this constant force because the tension requires forces applied in both ends. This tension limitation due to end-effector mass could also be projected to the end-effector feasible wrench set, having a wrench working range depending on the gravity force. Practically, when the end effector has low mass, the downward force exerted by the weight of the end effector may be too weak to maintain high tension in the cables during the motions that generate a strong wrench at the end effector. This constraint on the end effector wrench must be considered alongside the cable tensions because it could be a source of fault conditions that could be solved, for instance, by increasing the load of the platform.

In other words, designers cannot know a priori whether the suspended CDPR will fail due to an extreme cable tension or an extreme sum of vertical components of tension that are supporting the effector's weight. Therefore, the distribution of cable tensions must be designed considering the maximum vertical wrench exerted at the end effector, in addition to the upper and lower constraints on cable tension. Once the tension boundaries are designed in according to the suspended configuration limitations, actuators can be selected without over dimension risks, having a balanced set of requirements between the motors, tension boundaries and wrench feasibility in the platform.

The importance that the redundancy has in this project to provide soft and continuous tension distribution and secondary tasks was expressed in section 2.1. This justifies the need for a deeper analysis of its relation with suspended configuration. Following the methodology shown in chapter 1, a research of the state of the art is performed in section 2.2. In section 2.3, the objectives of the project were aligned with the hypothesis proposed attending to the state of the art to provide a method for handling the tension distribution with lower computation times based on the analysis of the maximum wrenches that a suspended CDPR can exert. The expressions for handling the tension distribution can be found in section 2.4 while in section 2.5 the optimal distribution required is defined and discussed. Section 2.6 focuses on the location of the maximum wrenches that can be applied in the end-effector, relating this wrench with the end-effector mass. Section 2.7 defines a fast RT algorithm to reach those wrenches maintaining a secure tension distribution. Theoretical and simulated results are provided in section 2.8 to check the feasibility of the method and they are discussed in section 2.9.

2.2. Related work

Redundancy is necessary to avoid collision, obstacles and singularities as observed in (Jean-Pierre Merlet, 1989) (Zlatanov et al., 1998), efficient motion optimization, workspace increase, optimization of dexterity, fault tolerance or satisfaction of some constraints were other advantages analyzed in (Dasgupta & Mruthyunjaya, 1998). Some of those imposed constraints allow the robot to be used for secondary tasks in serial robots like achieved in (Flacco et al., 2015) or in underwater vehicles as shown in (Antonelli & Chiaverini, 1998).

Several methods have been proposed for solving the tension distribution of redundantly constrained CDPR. One of the first methods to set cable tension higher than a minimum value was proposed in (Sadao Kawamura & Ito, 1993). Pott synthesized and compares different methods to calculate force distributions in cables in (Pott, 2014) (Pott, 2018).

Linear programming has been used to minimize the norm tension vector for all cables (Borgstrom et al., 2009) (Agahi & Notash, 2009) (Shiang et al., 2000) while quadratic programming was used to avoid discontinuities (Oh & Agrawal, 2005) (Tobias Bruckmann et al., 2006) (Agahi & Notash, 2009) and to test different p-norms (Snyman & Hay, 2004) (Verhoeven, 2004) (Clément Gosselin & Grenier, 2011), even considering the slack rope model as in (H. Li et al., 2013). A recursive dimension reduction algorithm is presented in (Pham, Yeo, et al., 2005) to check the equilibrium constraints like the force-closure, feasible wrench and wrench set conditions. Dykstra's alternating projection algorithm was used in (Hassan & Khajepour, 2007) and improved in (Hassan & Khajepour, 2008b). In (Taghirad & Bedoustani, 2011), a method based on iterative Karush-Kuhn-Tucker search is proposed and in (Lim et al., 2014) it is proposed a method based on modified gradient-projection.

In (Verhoeven & Hiller, 2002) (Tobias Bruckmann et al., 2007), the homogeneous problem is used to consider just the cable forces and discuss their continuity along a trajectory. This homogeneous solution that projects arbitrary vector into the null space of the Jacobian Matrix is used in (Saber, 2015). The null-space of the structure matrix can be used to set the tension distribution after imposing the maximum (Marc Gouttefarde et al., 2007) and minimum (P. Liu et al., 2014) tensions to prevent the cables from breaking or going slack. Currently, greater degrees of redundancy require more complicated and slower kinematics-planning algorithms as evidenced in (Lamaury & Gouttefarde, 2013a).

One non-iterative method is proposed in (Z. Cui, Tang, Hou, & Sun, 2019) based on Graham's scanning geometric calculations. This method allows to find the convex hull of a finite set of points to obtain the region of feasible tension distribution. Close-form (Pott et al., 2009) (Pott, 2014) and barycentric methods considering the feasible nullspace (Lamaury & Gouttefarde, 2013a) (Mikelsons et al., 2008) have been shown to be the fastest ways to maintain continuity in the wrench solutions and provide safe tension distributions as proposed in (Borgstrom, 2009). The barycentric method is based on the polytope of feasible tension calculated from the null space of the structure matrix that represents the restrictions of maximum and minimum tensions. An improved version of this method has been implemented for real-time motion planning for cable robots with two degrees of redundancy (M Gouttefarde et al., 2015) while in (Müller et al., 2014) the method is applied to three degrees of redundancy ($r = 3$).

Many researchers have defined lower and upper tension limits for the cables according to different criteria (Tobias Bruckmann et al., 2006) (Mikelsons et al., 2008) (Borgstrom et al., 2009) (Pott et al., 2009) (Pott, 2014) (M Gouttefarde et al., 2015). Agahi et al. didn't define a maximum-tension constraint and aimed to minimize the value of the square of the cable tensions to maintain continuity (Agahi & Notash, 2009). Oh et al. imposed boundaries in the null space and also aimed at the minimization of tension values (Oh & Agrawal, 2005). In (Rasheed et al., 2018), those boundaries allow to handle the stability of the mobile bases of the robot. In (Bouchard et al., 2010) Bouchard et al. analyzed a method based on zonotopes and found that the available wrench set is open and convex if there aren't upper tension boundaries.

The end-effector position and velocity can be obtained from the corresponding cable elongation and speed with the forward kinematics (FK), while the inverse kinematics (IK) obtains the corresponding cable length

and velocity according to the respective platform values. Considering redundantly constrained parallel robots, the IK can be obtained in a direct way (Roberts et al., 1997), however the FK is overdetermined because it has more information from cable position than the required by the end-effector. To solve the FK, in (Jeong et al., 1998)(Yang et al., 2004)(Aref, Oftadeh, et al., 2009) (Pott, 2010) optimization and numeric methods are used, in (J-P Merlet, 2004)(Berti, 2015) a method based on interval analysis is used while in (Von Zitzewitz et al., 2010) a method based on physical vibration is developed to provide a better understanding of the time needed to solve the optimization problem. The elasticity of the cables are included in the FK and IK calculation and deeply analyzed in (J. P. Merlet, 2008).

Cable model is fundamental for computational simulations to obtain accurate results and also for the real prototype to design effective control algorithms. Different cable models are presented in chapter 1. Elasticity is needed to control the tension distribution as shown in (J. Merlet, 2012) so in this redundant analysis, cables are modeled as massless linear springs. This model can be justified in real prototypes by using light and elastic materials like polymers, whose kinematics relations were analyzed in (V. L. Schmidt, 2017), or also by using materials with high Young modulus, like steel, with reduced cable section and imposing the elastic term attaching springs between the cable and the platform. If the attached springs have significant lower stiffness than the cable, the total cable stiffness can be modeled as the one of the springs. The first method ensures a low cable mass but the elastic value use to present non-linear effects (Jean-Pierre Merlet, 2009a) while the second method has an invariant elastic value and concentrated on the attached elastic material with the disadvantage of a relatively high mass in the cable. Cable mass will impose additional dynamics in the system and also create a sagging effect (Yuan et al., 2015), which is normally defined with catenary expressions (Marc Gouttefarde et al., 2012)(Nguyen et al., 2013). Assuming massless elastic cables, the tension distribution can be applied along more than 6 cables due to the higher range of tension values. In (Su et al., 2001), linear elastic models are applied for large CDPR concluding that this model could be appropriate for those cases where the end-effector has a high load.

In addition to the cable, the spool where it is coiled is another element that requires an appropriate model for an accurate kinematic and force distribution model. In (H. Liu & Gosselin, 2009), a prototype that doesn't requires cable coiling around winches is proposed. Considering this pulley influence in (V. Schmidt & Pott, 2013) FK is solved and in (Marc Gouttefarde et al., 2014) the sagging effect is also added to the model with spools.

The cable tension distribution requires to consider cable elasticity and force coupling (Kraus et al., 2013). This tension measurement can be made by using force sensors in the platform, in the last pulley, or before the last pulleys as compared in (Kraus, Kessler, et al., 2015). However, the control of the cable tension distribution imposes elastic deformations that makes necessary to perform simultaneous tension and length control in cables, what is known as a geometrico-static problem (Carricato, 2013). In (Kraus, 2016), force control of CDPR with elastic cables is analyzed where synchronous position and force controls are proposed. In (Z. Cui, Tang, Hou, & Sun, 2019) a real parallel processing is performed with a FPGA to handle this problem by controlling the small deformations of cables and obtaining a small error in tension.

2.3. Hypothesis and objectives

Knowing that the suspended configuration imposes a restriction in the tension values of the cables, this chapter aims to develop a method for obtaining the maximum end-effector wrenches that a suspended cable robot can apply in any desired direction in the space if the maximum cable tension is unbounded. The study of those maximum wrenches could be known to perform in latter chapters an appropriate synthesis and design of the CDPR with the required forces and torques that the platform has to exert to simulate the underwater conditions.

In addition, an efficient method to exert those maximum wrenches in a fast and secure way is required and analyzed in this chapter. This fast algorithm could help to simulate impact forces and accelerate the computation time in lower processors that handle multiple tasks. This proposed tension planner aims to reach the maximum end-effector wrench from its equilibrium state where the platform is not moving and under just the gravity force for CDPR with degree of redundancy = 2. This could be made by using the feasible regions of tension distribution from the nullspace of the structure matrix (M Gouttefarde et al., 2015). Reaching those two main objectives: maximum wrenches in suspended CDPR with unbounded upper tension, and a fast tension planner to reach them, the requirements for the CDPR respect maximum wrenches and the ability to exert them in a fast way could be followed attending to the restriction imposed by the suspended configuration.

The results and methods presented in this section could also be useful for sizing general lightweight cable-driven robots or those that need to perform powerful wrenches in constrained directions. These tasks include construction (Mattern et al., 2016) or industrial processes (Alias et al., 2018), where strong wrenches are applied in different directions, like drilling holes in curved walls, where the robot needs to be able to move to the wall and apply strong torque in any direction. Also hammering or pressing processes require high forces at the end effector pointing in different directions. Knowing the maximum needed wrench will serve to select appropriate actuators and upper limit boundaries considering restriction imposed by the suspended configuration. In some cases, the

desired wrench cannot be produced for a certain pose without introducing undesired vertical forces that displace upwards the end effector so designers may also need to add weight to the end effector to balance the vertical components of the cable tensions or move to an appropriate pose.

The first hypothesis proposes that the consideration of the maximum vertical force supplied by gravity can be used to close the open Available Wrench Set defined in (Bouchard et al., 2010) when undefined maximum tensions are imposed. In that research, unbounded cable tensions provide open sets of the Available Wrench Set that could be set by imposing tension limits to the cables, generating a zonotope. If the nullspace polytope of feasible tension distribution is obtained by imposing maximum and minimum tension boundaries, the maximum wrench that the end effector can reach with the limited gravity force won't be known and that wrench will be related with a specific tension distribution that could be feasible or not, according to the tension boundaries defined. Both scenarios present problems: if the maximum wrench that the gravity force can handle is inside the cable tension boundaries, the maximum cable tension could be oversized because the platform cannot exert that. On the other hand, if the maximum wrench is outside the feasible tension range, the wrench capability of the robot will be reduced due to the cable and actuator limitation. If the end effector is heavy enough in comparison with the forces applied, the tension boundaries imposed could include all the feasible wrench applicable to the suspended platform. However, if the effector is relatively light, it is likely to be pulled upward and out of the desired position before any of the cables reach their maximum tension.

The second hypothesis affirms that it is possible to define and calculate the tension trajectory to reach any desired maximum wrench that requires the minimum computation time based on taking the minimum number of set points ensuring that all cables will remain between their boundaries. As seen in (Pott, 2018), there are some methods to achieve in real-time the tension distribution for one specific configuration. However, there are situations that require to reduce the computation of a big amount of points like in those situations where several secondary processes are being developed by the computer or when faster velocities are required like impact wrenches. During the motion from the initial configuration to the maximum wrench, the wrench will vary from its initial to its maximum value. This process will displace the polytope of feasible tension distributions and changes its shape. The path planning algorithm that accomplishes this change needs to plan the path quickly while keeping the tension distribution inside the feasible polytope. Since this algorithm does not need to search through multiple samples, it can direct the robot to exert its maximum effort rapidly. The planned trajectory is defined in the null space of the structure matrix of the robot and can be combined with usual trajectory planners that are defined for the end effector's degrees of freedom to define a path planner with two degrees of freedom.

Main chapter's objectives:

1. Develop a method and discuss for detect the maximum wrenches in the end-effector of suspended CDPRs with unbounded upper tension.
2. Increase the speed of the tension planner considering the redundancy to achieve those maximum wrenches of the end-effector in the minimum time.

Chapter's hypotheses:

1. The maximum vertical force supplied by the weight of the end-effector can be used to close the open Available Wrench Set defined in (Bouchard et al., 2010) maintaining the cable tensions unbounded.
2. A fast tension planner is possible to define by reducing the number of samples guaranteeing the secure tension condition.

2.4. Cable tension configuration

Cable robots with redundant actuators ($n + 1 < m$) have over-determined forward kinematics and under-determined distribution of forces, which can be illustrated with a consideration of the linear application defined by the robot's Jacobian matrix. This Jacobian matrix can be calculated by deriving the geometric close-form equation of the cables and end-effector, or calculated by using screw theory (M Gouttefarde et al., 2015). The reference point is defined for twists and wrenches at the geometrical center of the effector (O'). Fig. 1 illustrates the magnitudes involved in the Jacobian matrix. Two reference frames are relevant: a fixed reference frame $\{F\}$ and a mobile reference frame $\{M\}$, which is attached and linked to the effector.

Points $\{A_1, A_2, \dots, A_n\}$ are the positions of pulleys that anchor the cables. $\{B_1, B_2, \dots, B_n\}$ are the points on the end-effector to which the cables are attached. $\{u_1, u_2, \dots, u_n\}$ are unit vectors pointing in the direction of each cable. $\{p_1, p_2, \dots, p_n\}$ define the distance from the geometric center of the end effector to the attachment points. $\{l_1, l_2, \dots, l_n\}$ are the length of the cables.

The wrench imposed by a single cable i on the end effector, as it appears to O' , is:

$$\zeta_i = \begin{bmatrix} \mathbf{u}_i \\ \mathbf{p}_i \times \mathbf{u}_i \end{bmatrix} (-\tau_i) \quad (2.1)$$

The negative sign with the cable tension indicates that the cables are pulling.

Figure 2.1 Scheme of geometric magnitudes needed to define the Jacobian matrix of a cable robot. $\{F\}$ is the fixed frame and $\{M\}$ moves with the end effector

Since this general robot scheme is a parallel manipulator, the total wrench in O' is the span of the wrenches driven by all cables (Bouchard et al., 2010).

$$\begin{bmatrix} -\mathbf{F} \\ -\mathbf{M}_{O'} \end{bmatrix} = \begin{bmatrix} \mathbf{u}_1 & \cdots & \mathbf{u}_n \\ \mathbf{p}_1 \times \mathbf{u}_1 & \cdots & \mathbf{p}_n \times \mathbf{u}_n \end{bmatrix} \begin{bmatrix} \tau_1 \\ \vdots \\ \tau_n \end{bmatrix} \quad (2.2)$$

$$\begin{bmatrix} -\mathbf{F} \\ -\mathbf{M}_{O'} \end{bmatrix} = \mathbf{A} \boldsymbol{\tau} \quad (2.3)$$

Where $\boldsymbol{\tau}$ represents the cable tensions, $\mathbf{F}$ and $\mathbf{M}_{O'}$ represents the end-effector forces and torques effected by those cable tensions, respectively, O' is the reference point, and $\mathbf{A}$ is the wrench matrix. All the wrenches are defined by active forces and no additional wrenches are imposed by kinematic restrictions, the wrench matrix, also called structure matrix, is equivalent to the transpose of the Jacobian $\mathbf{J}^T$. By using the principle of virtual work, the Jacobian matrix ($\mathbf{J}$) can be defined as (Ghasemi et al., 2009)(Taghirad, 2013):

$$\begin{bmatrix} \dot{l}_1 \\ \vdots \\ \dot{l}_n \end{bmatrix} = \begin{bmatrix} \mathbf{u}_1 & \mathbf{p}_1 \times \mathbf{u}_1 \\ \vdots & \vdots \\ \mathbf{u}_n & \mathbf{p}_n \times \mathbf{u}_n \end{bmatrix} \begin{bmatrix} v_o \\ \boldsymbol{\omega} \end{bmatrix} = \mathbf{J} \begin{bmatrix} v_o \\ \boldsymbol{\omega} \end{bmatrix} \quad (2.4)$$

The resulting Jacobian matrix is equivalent of the Stewart- Gough platform. The main difference is that the actuators cannot apply compressive strength to cables so they must always be under positive tension. A suspended robot cannot be controlled with loose cables, which are release from the kinematic chain once they achieve that condition. This constraint on the cable tensions is defined with a minimum tension limit:

$$\begin{bmatrix} -\mathbf{F} \\ -\mathbf{M}_{O'} \end{bmatrix} = \mathbf{A} \boldsymbol{\tau} = -\mathbf{W} \quad (2.5)$$

$$\text{with } 0 < \tau_{min} < \tau_i \quad i \in [1, m]$$

The suspended configuration has the end effector hanging from the cables in static equilibrium, in which all cables pull the platform to balance its weight. The only force acting on the end-effector with a component in the downward direction is its own weight. Knowing this fact, it is possible to write the left-hand term of (2.5) as (P. Bosscher et al., 2007):

$$\begin{bmatrix} \mathbf{F}_R \\ \mathbf{M}_{0_R} \end{bmatrix} = \begin{bmatrix} \mathbf{F} \\ \mathbf{M}_O \end{bmatrix} + \begin{bmatrix} \mathbf{F}_E \\ \mathbf{M}_{0_E} \end{bmatrix} \quad (2.6)$$

$$\mathbf{A}\boldsymbol{\tau} = \begin{bmatrix} \mathbf{F}_E \\ \mathbf{M}_{0_E} \end{bmatrix} - \begin{bmatrix} \mathbf{F}_R \\ \mathbf{M}_{0_R} \end{bmatrix} \quad (2.7)$$

$$\text{with } 0 < \tau_{min} < \tau_i, \quad i \in [1, m]$$

Where $\mathbf{F}_E$ and $\mathbf{M}_{0_E}$ are the force and torque imposed on the end-effector due to external forces, respectively. $\mathbf{F}_R$ and $\mathbf{M}_{0_R}$ are the resultant force and torque when all wrenches on the effector are considered, respectively. The external wrench considered in this analysis comes from the gravitational force acting on the effector from its center of mass. Dynamic efforts are not considered in this analysis assuming that the end-effector movement is negligible, as justified section 2.3. The position of this center of mass relative to the geometric center of the effector is defined by the vector $\mathbf{p}_G$. In this way, the external wrench imposed by gravity is defined as (Marc Gouttefarde et al., 2015):

$$\begin{bmatrix} \mathbf{F}_E \\ \mathbf{M}_{0_E} \end{bmatrix} = \begin{bmatrix} m\mathbf{g} \\ \mathbf{p}_G \times (-m\mathbf{g}\mathbf{k}) \end{bmatrix} \quad (2.8)$$

In this equation, the external force in the vertical axis is always pointed downward. This external wrench can be considered as a virtual cable that pulls the effector downward with constant force. Considering (2.2), and because the robot has suspended configuration, the third row of $\mathbf{A}$ is always lower than zero because the vertical component of the tensions exerted by the cables is pointed upward. Along with (2.7) and (2.8), this fact allows us to express the boundary conditions on a suspended cable robot with the following equation for the vertical axis in the fixed reference frame:

$$\sum_{i=1}^m u_{iz}\tau_i = -F_Z = mg_z - F_{R_z} \quad (2.9)$$

$$\text{with } \left(\sum_{i=1}^m u_{iz}\tau_i \right) < 0$$

Equation (2.9) defines the characteristic condition for suspended cable robots. This balance of wrenches is illustrated in Fig. 2.2. Because of the suspended configuration, the vertical force provided by cables to the platform, $(-F_Z)$, is always positive, therefore, it always points upward.

Figure 2.2 Scheme of forces applied to the end effector by cables and the resultant force.

The downward force can only be applied by gravity. The vertical motion of the end effector is constrained as follows:

$$mg_Z < F_{R_Z} \quad (2.10)$$

Equation (2.10) is obtained directly from (2.9) and means that a suspended cable-driven robot cannot be driven with a downward vertical force greater than its own weight. This constraint is valid if every anchor on the effector is situated under its corresponding cable pulley and no external forces other than gravity act on the system. The limitation set by (2.9) also imposes an upper limit on τ . Rewriting (2.9) makes this constraint clear:

$$F_Z = F_{R_Z} - mg_Z \quad (2.11)$$

As tension increases, F_Z increases to balance the weight of the end effector. If the resultant vertical force is to be kept constant, F_Z must be constant. Considering the special configuration of the Jacobian for a suspended cable robot, in which all vertical components are negative, the tension distribution in the cables has to satisfy (2.9).

2.5. Optimum tension distribution

Due to the number of actuators than DoF of the platform, the wrench matrix ($\mathbf{A}$) is not square and its tension distribution under-determined. For a given wrench at the end effector, therefore, an infinite number of tension distributions can be used to generate that wrench. Those tension configurations can be calculated with the following equation (Flacco et al., 2015)(Verhoeven, 2004):

$$\tau = \mathbf{A}^\dagger(-\mathbf{W}) + \mathbf{N}\lambda = \tau_0 + \tau_h \quad (2.12)$$

$\mathbf{A}^\dagger$ is the Moore-Penrose pseudoinverse of $\mathbf{A}$, $\mathbf{N}$ is an $m \times r$ matrix representing the null-space of the Structure matrix and $\lambda = [\lambda_1, \dots, \lambda_r]^T$ is an arbitrary vector that lets us determine any tension configuration. $\mathbf{N}$ is the basis of the null space of the structure matrix ($\mathbf{A}$), which can be obtained using QR decomposition or the singular-value-decomposition (SVD) method (Foster, 1986). τ_0 provides the particular solution for the tension configuration with the lowest 2-norm. However, some tensions included in this particular solution may have negative values, which means that the cable will go slack. The homogeneous solution τ_h prevents this situation and ensures that the calculation yields a valid tension configuration with all cables pulling the load.

The null space can be calculated more quickly with the projection of any tension set onto the nullspace of the structure matrix, as follows.

$$\boldsymbol{\tau} = \mathbf{A}^\dagger(-\mathbf{W}) + \mathbf{P}\boldsymbol{\tau}_N \quad (2.13)$$

$$\mathbf{P} = (\mathbf{I} - \mathbf{A}^\dagger\mathbf{A}) \quad (2.14)$$

$\mathbf{P}$ is the $m \times m$ orthogonal projector of the structure matrix ($\mathbf{A}$) and $\boldsymbol{\tau}_N \in R^m$ is the generic tension distribution of m cables. Though this method is faster and is commonly used, it requires an m -dimension vector ($\boldsymbol{\tau}_N$) and an m -dimension hyperplane. In this thesis, eq. (2.12) is used to calculate tension distributions, which considers only the r -dimension basis of the null space, instead of the m -dimensional tension vector. Although this method requires a QR or SVD decomposition, only the r values that span the decomposed basis are needed to set the feasible tension distribution with a redundantly actuated system.

Detailed analysis of (2.12) shows that the value of $\boldsymbol{\tau}_0$ depends on the wrench matrix and the external forces applied to the end-effector. The particular solution for the cable-tension configuration is a function of the direction of the cables $\mathbf{u}$, the relative position of the effector anchors $\mathbf{p}$, and the external force $\mathbf{f}$:

$$\boldsymbol{\tau}_0 = \mathbf{g}(\mathbf{u}, \mathbf{p}, \mathbf{W}) = \mathbf{A}^\dagger(-\mathbf{W}) \quad (2.15)$$

Turning to the second term in (12), the null space of the wrench matrix maintains the relations of the Jacobian matrix. The homogeneous solution of the cable-tension configuration is therefore a function of $\mathbf{u}$, $\mathbf{p}$ and $\boldsymbol{\lambda}$:

$$\boldsymbol{\tau}_h = \mathbf{h}(\mathbf{u}, \mathbf{p}, \boldsymbol{\lambda}) = \mathbf{N}\boldsymbol{\lambda} \quad (2.16)$$

This study is focused on determining the maximum wrench that can be safely applied to the end effector. If the position of the end effector is fixed, $\mathbf{u}$ is a constant parameter and $\mathbf{p}$ is also constant if the end-effector anchors maintain their positions relative to each other. The remaining variables are $\mathbf{W}$ and $\boldsymbol{\lambda}$, the calculation of which are the focus of the following sections.

2.5.1. Region of feasible tension configurations (Ω)

This subsection is based on the work from (Pott et al., 2009) and (M Gouttefarde et al., 2015). However, the present analysis focuses on the limitation imposed by the weight of the effector, as defined in Eq. (2.9), instead of focusing on the constraint of the maximum allowed cable tension. Taking the general expression for cable tension (2.12) with constraints of only the minimum tension values (2.7) and the boundary conditions (2.9), the following expression results:

$$\begin{aligned} \boldsymbol{\tau}_{min} - \mathbf{A}^\dagger(-\mathbf{W}) &\leq \mathbf{N}\boldsymbol{\lambda} \\ \text{with } \sum_{i=1}^m u_{iz}\tau_i &= mg_z - F_{R_z} \end{aligned} \quad (2.17)$$

Eq. (2.17) only requires a minimum tension value to calculate the maximum-allowed cable tension that keeps the robot in a suspended configuration. Eq. (2.17) also can give the value of the highest wrench that can be applied to the end-effector.

Because the degree of redundancy is r , $\mathbf{N}$ is an $m \times r$ matrix that defines m r -dimensional polytopes in an $(r + 1)$ -dimensional space. The space of representation of the polytopes has an extra dimension that represents the tension in each cable with Eq. (2.12). This representation ensures that one axis always corresponds to a tension values so that the minimum tension constraint is easy to choose. The r remaining dimensions of the representation space define working points in the r -dimensional space orthogonal to the dimension that represents tension values, already used in the experimental analysis from (Ghanbari et al., 2018).

A system with the degree of redundancy $r = 2$ is easier to solve, so the case of an end effector with $n = 6$ DoF with $m = 8$ cable actuators is analyzed. The aim is to maximize the wrench that can be exerted in any direction under the constraint of the weight of the platform. With this consideration, the 8 polytopes have two dimensions so they are planes represented in a 3D space where also the tension values are included. The vertical axis represents the tension in any cable while the base plane represents the working point defined by $\boldsymbol{\lambda} \in R^2$. If any value of $\boldsymbol{\lambda}$ provides a tension value equal to τ_{min} , this value of $\boldsymbol{\lambda}$ corresponds to the boundary of the region of

valid tension configurations (Ω). If λ lies inside the valid region, all the planned tensions of the eight cables are allowed.

Figure 2.3 A) Example of the polytope representation of possible tensions in eight cables with a 6-DoF end effector with minimum tension in each cable of 0 N and maximum tension of 700 N. λ can have any value inside the polytope boundary. Once a value of λ is defined, the vertical coordinate in plane for the given λ values is the applied tension. B) The yellow area represents the region in which λ provides positive tension values.

Each plane defines a set of valid tensions in each cable. The vertical axis defines the tension in each cable and horizontal axes represent the parameters in λ that select a valid tension configuration from the homogeneous solution. Fig. 2.3 shows an example of a representation of the valid region of possible tension configurations for an end effector located in $\chi = [5, 3.5, 1]$ meters measured from one low corner of a parallelepiped robot of $10 \times 5 \times 6$ meters. The end effector is a cube 1-meter side and an external wrench of $\mathbf{W}_E = [1000, 0, -150 \cdot 9.8 \mid 0, 0, 0]$ [N|N·m] acts on the effector. This representation was calculated using numerical methods and shows one plane for each cable that represents the tension applied. The tensions in all cables can be modified by changing the values of λ . Note that for $\lambda = [0, 0]^T$ no valid tension configuration for cables is returned. This point corresponds to the particular solution obtained with the Moore-Penrose pseudoinverse since the homogeneous term of the tension configuration is zero in this case. This case illustrates that the homogeneous solution is needed to reach a valid tension configuration for some locations and wrenches of the end effector.

2.5.2. Vertex computation of Ω

To increase the accuracy and speed of the tension distribution calculation, an algebraic method is used to find appropriate values of λ . The feasible region of λ can be obtained using the agile algorithms developed in (Pott et al., 2009) or in (M Gouttefarde et al., 2015), considering that the robot has redundancy $r = 2$.

Figure 2.4 Example of a two-dimensional polytope that corresponds to the tension in one cable as a function of the value of λ_1 and λ_2 which are constrained to the horizontal plane.

Since the system has a degree of redundancy of two, the null space is represented as eight planes (Π). Any point of these planes can be selected by choosing the values of λ . One of these planes (Π_i) is illustrated in Fig. 2.4. The plane i can be defined in Hessian normal form as:

$$\Pi_i \equiv \mathbf{n}_i \mathbf{x} = [n_{i1} \quad n_{i2} \quad n_{i3}] \begin{bmatrix} x_{i1} \\ x_{i2} \\ x_{i3} \end{bmatrix} = p_i \quad (2.18)$$

In this representation, $\mathbf{n}_i$ is the normal vector of the plane, $\mathbf{x}$ is a point in the plane and p_i is the shortest distance to the plane from the origin. The normal vector $\mathbf{n}_i$ can be taken directly from the null-space matrix N .

$$\mathbf{n}_i = [1, 0, N_{i1}] \times [0, 1, N_{i2}] = [-N_{i1}, -N_{i2}, 1] \quad (2.19)$$

The distance from the origin to plane i is defined by taking a point in the plane and projecting it to the normal vector. A known point of the plane gives the particular solution of the tension configuration:

$$\mathbf{p}_i = \mathbf{n}_i \cdot [0, 0, \tau_{0i}]^T \quad (2.20)$$

Eqs. (2.18), (2.19) and (2.20) describe the planes that define the configuration of cable tensions. With these equations, the lines of intersection between the eight planes of the null space and the horizontal plane can be obtained, and these define the minimum admissible tension in the cables. The plane of the minimum tension limit is defined as:

$$\Pi_{\tau_{min}} \equiv [0 \quad 0 \quad 1] \cdot \begin{bmatrix} x_{r1} \\ x_{r2} \\ \tau_{min} \end{bmatrix} = \tau_{min} \mathbf{k} \quad (2.21)$$

The intersections between the null-space planes and the minimum tension plane are described using a point and a unit vector:

$$\mathbf{l}_i = \mathbf{l}_{0i} + \mathbf{dir}_i \mu_i \quad (2.22)$$

The direction of the intersection of two planes is perpendicular to the normal vectors of each plane:

$$\mathbf{dir}_i = \mathbf{n}_i \times [0, 0, 1]^T \quad (2.23)$$

One specific point of the intersection line, $\mathbf{l}_{0i}$, is obtained from the equation of the plane (2.18), setting the intersection of line $\mathbf{l}_i$ with the x-z plane and the distance from the origin to the plane equal to the minimum tension:

$$n_{ix} \cdot x_{ix} + n_{iy} \cdot 0 + n_{iz} \cdot \tau_{min} = p_i \quad (2.24)$$

$$\mathbf{l}_{0i} = \begin{bmatrix} x_{ix} \\ 0 \\ \tau_{min} \end{bmatrix} = \begin{bmatrix} \frac{p_i - n_{iz} \cdot \tau_{min}}{n_{i1}} \\ 0 \\ \tau_{min} \end{bmatrix} \quad (2.25)$$

This step defines eight lines of intersection between the planes in (2.22). The next step is to find the intersections of the eight lines, which serve as candidates for the vertices of the polygon that bounds λ .

$$\mathbf{l}_i(\mu_{ij}) = \mathbf{l}_j(\mu_{ji}) \quad (2.26)$$

Where μ_{ij} is the value of the direction of line i that defines a point in line j . The intersection between lines i and j is V_{ij} .

$$\mathbf{V}_{ij} = \mathbf{V}_{ji} = \mathbf{l}_0 + \mathbf{dir}_i \cdot \mu_{ij} \quad (2.27)$$

Figure 2.5 Representation of two planes, Π_i and Π_j , corresponding to the tension of cables i and j for any value of λ_1 and λ_2 . Their intersection with the plane of minimum tension, $\Pi_{\tau_{min}}$, defines the lines $\mathbf{l}_i$ and $\mathbf{l}_j$ that are candidates to be boundaries of the region of valid tension configuration.

These vertices need to be compared with the frontier of the polygon of valid solutions. To rule out those vertices inside the polygon, two close values to the vertex in the same direction of the line i must be defined:

$$\mathbf{V}_{ij}^+ = \mathbf{l}_0 + \mathbf{dir}_i \cdot (\mu_{ij} + \epsilon) \quad (2.28)$$

$$\mathbf{V}_{ij}^- = \mathbf{l}_0 + \mathbf{dir}_i \cdot (\mu_{ij} - \epsilon) \quad (2.29)$$

A small scalar (ϵ) is defined to provide a value close to the vertex. The number of intersection points is $C_{8,2} = 28$. Only a few of them conform to the polygon of admissible tensions. The intersection points that satisfy (2.30), which is based on (2.17), are chosen as the vertices of the polygon of admissible tensions (Ω):

$$\mathbf{V}_{ij}^* = \mathbf{V}_{ij} \Leftrightarrow \quad (2.30)$$

$$\left\{ \begin{array}{l} \tau_{min} - A^\dagger(-W) \leq NV_{ij} \\ (\tau_{min} - A^\dagger(-W) \geq NV_{ij}^+) \vee (\tau_{min} - A^\dagger(-W) \geq NV_{ij}^-) \end{array} \right\}$$

These conditions select only those vertices that are along the border of the polygon of valid λ , while leaving out those lying inside or outside of the polygon. The first condition validates a vertex if it is inside the polygon or on the border of the region of admissible values, Ω . The second condition is true if one of the points that lead to a configuration close to the vertex point cannot be reached with tension in the cables. That condition is only satisfied when the point matches with a vertex of the polygon of valid configurations.

With the polygon of valid tension configurations (Ω) defined, a valid working point must be chosen. Mikelsons et al.'s algorithm chooses the barycenter of the polygon (Mikelsons et al., 2008), but since we only need an appropriate feasible point in the very reduced polygon immediately around the maximum wrench region, a quick and useful working point is the Euclidean norm of the vector describing the valid vertex:

$$\lambda^* = \|V_{ij}^*\|_2 \quad (2.31)$$

The region of valid working points must be calculated to produce a valid tension configuration. This procedure must be repeated every time the parameters in Eqs. (2.15) and (2.16) change, excepting λ : the position of the effector, the position of the center of mass, or the wrench acting on the effector.

This section described how λ is selected when all the other parameters are constant. The next section proposes an algorithm that generates a λ to drive the effector to the maximum wrench in any direction, and returns the upper limit of that wrench, given the weight of the effector.

2.6. Maximum Wrench of Suspended CDPR

This section is focused on the calculus of the maximum wrench applicable at the end effector in any desired direction in the Special Euclidean algebraic group SE(3) (Park & Chung, 2005). The maximum wrench is defined in the task space of the robot, even though no maximum-tension constraint is defined ahead of the calculation. This maximum force limit is determined by the weight of the end effector.

The distribution of tensions needed is also calculated to exert the maximum wrench, so that the robot can provide from the forces of the static equilibrium to the maximum desired wrench.

2.6.1. One axis analysis

Considering (2.15), the particular solution for the tension configuration, from (2.12), varies with the position of the end effector, the position of the end-effector anchors, and external forces applied to the platform. Considering that the robot is suspended under the anchor points for its cables, the maximum wrench at the end effector is limited by the maximum vertical tension that is balanced by the weight of the effector as seen in (2.9). Though the following analysis assumes that the end-effector and its anchors are fixed, wrench variations are applied to the end-effector in both directions of each of the six DoF from the equilibrium state to the maximum force/torque along each DoF. These six axes are considered in the Special Euclidean algebraic group, SE(3) (Park & Chung, 2005).

Linear programming is used to find the values of the maximum forces and torques (wrenches) that can be exerted along each axis of the end effector. Above, Eq. (2.7) defined the relation between the wrenches exerted by cables, the external wrenches, and the resultant wrench. By maximizing the value of the resultant wrench with the limit of minimum cable tension and the restriction of the defined value of F_{RZ} , the maximum force or torque applicable in a specific axis can be calculated, as well as the maximum tension allowed in each cable. A similar procedure can be applied to minimize the resultant wrench to determine the upper limit of cable tension. The objective function to obtain the maximum force or torque along an axis is defined as follows:

$$\begin{aligned} & \max \xi_I \\ & \text{with } \begin{cases} A\tau = \begin{bmatrix} F_E \\ M_{0_E} \end{bmatrix} - \begin{bmatrix} F_R \\ M_{0_R} \end{bmatrix} \\ 0 \leq \tau_{min} \leq \tau_i \\ F_{RZ} = 0 \end{cases} \\ & n = \{1, 2, \dots, 8\} \end{aligned} \quad (2.32)$$

Where ξ_I is the resultant force or torque value in any axis except F_{R_z} which is set to zero: $\xi_I = \{F_{R_x}, F_{R_y}, M_{O_{R_x}}, M_{O_{R_y}}, M_{O_{R_z}}\}$.

Eq. (2.32) maximizes or minimizes the force or torque along one axis (whether in the positive or negative direction) in order to find the maximum force or torque without defining an upper limit for the cable tension. The first restriction was defined in Eq. (2.7). Monovariate optimization can be applied to determine the resultant force or torque in each case, setting the rest of axes to null. In Eq. (2.32), no optimization is performed in the vertical axis F_{R_z} because its value is forced to zero. Force optimization over the vertical axis would be unbounded, as seen in Eq. (2.9), because a desired force can be generated without changing the force applied along any other axis. The maximum downward force in this axis was obtained in Eq. (10), and it is due only to the weight of the end-effector. If the cable robot is designed to exert its maximum vertical force, upper limits need to be imposed on the cable tension.

Six different upper and lower limits for W_R were obtained for each 6-dimension axis of force and torque. When the maximum force or torque in any axis is exceeded three different faults can appear in this situation, depending on which of the optimization constraints has been violated:

- a) one or more cables goes slack.
- b) an undesirable and uncontrolled vertical force appears.
- c) both fault effects occur at the same time.

Control is lost if any of the cables go slack because the kinematic equations of the system consider only tensed cables. A loose cable, then, is equivalent to a disconnected cable. The developed algorithm addresses this problem of overstepping the maximum wrench limits by forcing a minimum tension in the cables if a negative tension arises in the planned tension distribution. This correction alters the cable tension configuration from the desired distribution so, according to Eq. (2.9), because the effector's mass and position are constant, an undesired upward force is generated due to the compensation of the slack cable.

λ is important once the maximum wrench is calculated because λ defines the position in the null space basis that allows the end effector to exert maximum force along the axis in question. λ_{opt}^F is the value in null space basis that generates the maximum force or torque along a specific axis at a given end-effector position. This parameter is useful when the robot attempts a specific task inside the workspace that requires a large wrench in any direction. The first time such a task is planned, the linear optimization in Eq. (2.32) must be applied to determine the value of the specific maximum wrench. The value of the λ_{opt}^F can be calculated once the maximum wrench is known. Once this value is known, the robot only needs to go to the position in null space given by λ_{opt}^* if the platform is in the same position as in the first analysis. Using the general equation for cable-tension distribution (Eq. (2.12)), the null space point that provides the calculated maximum wrench is:

$$\lambda_{opt}^F = N^+(\tau - A^+(-W_{max})) \quad (2.33)$$

The value of λ_{opt}^F is the value of λ that effects the maximum desired wrench. To reach this configuration, an algorithm should consider values of λ that are close to or equal to λ_{opt}^F . This value can also be obtained by applying the method described in section 2.3, which imposes the already known maximum wrench. Because the LP of Eq. (2.32) has been used, the maximum wrench at the end effector can be generated by using only one tension distribution, which is defined by λ_{opt}^F .

2.6.2. Analysis in arbitrary direction

In the previous section, the maximum wrench was analyzed in only one axis to present a simplified version of the process. This section extends that analysis to a generalized wrench that points in any of the 6 dimensions of the SE(3) space to find the maximum force or torque that can be applied in that direction. The given direction of the wrench is $A = [x_A, y_A, z_A, \alpha_A, \beta_A, \gamma_A]^T$, with the first three terms in linear coordinates and the last three terms in angular coordinates.

$$\max \xi_{II} \quad (2.34)$$

$$\text{with } \left\{ \begin{array}{l} \mathbf{A}\boldsymbol{\tau} = \begin{bmatrix} \mathbf{F}_E \\ \mathbf{M}_{0_E} \end{bmatrix} - \boldsymbol{\Lambda}\xi_{II} \\ 0 \leq \tau_{min} \leq \tau_i \\ F_{R_z} = z_{\Lambda}\xi_{II} \end{array} \right\}$$

$$n = \{1, 2, \dots, 8\}$$

Equation (2.34) calculates the maximum wrench in the direction of $\boldsymbol{\Lambda}$. In this generalization of the wrench direction, the magnitude of the effort (ξ_{II}) is maximized to determine its maximum value in the direction of $\boldsymbol{\Lambda}$. In this case, the restrictions are the wrench-closure equations, the minimum tension in cables to prevent looseness, and the requirement that the vertical force not exceed the weight of the end effector. One additional condition is needed to ensure that the optimized solutions are bounded:

$$\begin{aligned} \boldsymbol{\Lambda} &\neq [0, 0, k, 0, 0, 0]^T \\ k &\in \mathbb{R} \end{aligned} \quad (2.35)$$

As seen in equation (2.34), if the desired wrench produces only a vertical force, the optimization problem is not bounded because no force internal to the system affects the vertical force. Considering the exception imposed by equation (2.35), the desired forces or tensions in the other directions yield a closed set of tension distributions.

Once the maximum torque or force is obtained for the direction in question, $\boldsymbol{\lambda}_{opt}^F$ must be determined so that the manipulator can exert the tension distribution smoothly, and the calculation proceeds using Eq. (2.33), as above.

2.7. Null-Space Tension Planner

The tension planning process is defined in the null space. Trajectories along this space represent variations in the configuration of tensions in the cables. The null space is used to analyze the process by which the manipulator can exert the maximum wrench at the end effector from its equilibrium state. The target of this trajectory was defined above as $\boldsymbol{\lambda}_{opt}^F$. The initial position and wrench ($\boldsymbol{\lambda}_{opt}^0$) is obtained by using the method described before.

Figure 2.6 Three different region of valid tension configuration Ω_0 , Ω_1 and Ω_F corresponding to the application to an initial wrench ($\mathbf{W}_0$), a wrench value between the initial and the maximum ($\mathbf{W}_i$), and the maximum wrench ($\mathbf{W}_{max}$). It is also shown the optimum point of working inside each Ω : $\boldsymbol{\lambda}_{opt}^0$, $\boldsymbol{\lambda}_1^*$ and $\boldsymbol{\lambda}_{opt}^F$. (Shapes and scales don't correspond to a real case)

The region Ω is defined by using the planes Π_i from eq. (18). These planes depend on both components of the cable tension: $\boldsymbol{\tau}_0$ and $\boldsymbol{\tau}_h$, with the dependent variables defined in eq. (2.15) and eq. (2.16). As we are considering the end-effector in the same position, the region of valid tension distribution varies only with the value of $\mathbf{W}$, modifying the range of feasible $\boldsymbol{\lambda}$ values. As seen in Fig. 2.6, to go from the application of $\mathbf{W}_0$ to the application of $\mathbf{W}_{max}$. It is possible to obtain as many intermediate regions Ω_i as intermediate wrench $\mathbf{W}_i$, I would like to consider ($i = 1, 2, 3, \dots$). Although the process for obtaining each one of these feasible regions, Ω_i , has been improved reducing its time consuming, a big amount of Ω_i calculations for exerting fast rearrangement of tension

could take more time than the needed. That is why in this section it is proposed a method to reduce the number of Ω_i to the minimum to be able to reach $\mathbf{W}_{max}$ in a faster way.

Figure 2.7 Scheme for calculating the tension configurations, λ_i^* , of the null space path planning.

2.7.1. Tension distribution trajectory

At the beginning, when initial wrench is applied, the polytope Ω_0 is calculated. Next, the algorithm calculates the λ_{opt}^F that defines the tension distribution to produce the desired wrench and position, and calculates the corresponding polygon of feasible tension distributions Ω_F . Once the two polygons of feasible tension configurations are calculated (for the initial and final wrenches), the algorithm checks if the two polygons intersect, if one polygon is inside the other, or if they are disjoint with no common points, as illustrated in Fig. 2.6.

a) Intersecting polygons:

In this case, an intermediate value of λ for the transition between the initial λ_{opt}^0 and final λ_{opt}^F tension distribution can be found. The vertex computation is applied to the vertices of the polygon defined by the intersection between the adjacent polygons of initial and final feasible tension configurations. This method produces the optimum value for the intersection λ_{opt}^I . The resulting trajectory has three set points.

b) One polygon inside the other:

When one polygon is inside the other, no additional set points are needed during the tension planning because the trajectory can be reduced to one single point: λ_{opt}^0 or λ_{opt}^F . The choice depends on which provides feasible trajectories during the entire transition.

c) Disjoint two exterior polygons:

If the two polygons have no points in common, the trajectory between the initial and final tension configuration cannot be traversed directly. In order to avoid analyzing multiple samples of $\mathbf{W}$, only one intermediate point (λ_{opt}^I) is defined as a set point in the null space using Eq. (35). This set point is used to test that the trajectory can be performed like in the previous two cases and it is obtained from an intermediate wrench value between the initial and the maximum:

$$\mathbf{W}_i = \frac{\mathbf{W}_j + \mathbf{W}_k}{2} \quad (2.36)$$

If there is no intersection between the polygon of the intermediate point (λ_{opt}^I) and the two adjacent polygons, another intermediate point (λ_{opt}^{II}) must be calculated by using Eq. (2.36) and substituting the optimal null-space points that provide two feasible polytopes that do not intersect. This process is iterated until every set

point (λ) provides a polygon that intersects with two other polygons to produce a continuous chain of feasible tension distributions from the first to the final set point.

2.7.2. Wrench estimations over the tension trajectory

Once all the set points have been determined (λ_i^*), the trajectory needed to exert the desired maximum wrench can be planned. If the plan includes more than one set point, a path through must be calculated from one set point to the next in the null space. The number of points in this path depends on the desired smoothness of the change of the cable tensions (more points) and the velocity that the process requires (less points). The corresponding tension values need to be calculated for each of the desired λ values.

When the wrench increases and the optimal tension distribution for that wrench is outside the initial feasible polygon, the speed of displacement of the point in the null space (λ_i^*) must be considered. If the speed is too low, the polygon may advance faster than λ and leave the polygon of feasible tensions (Ω_i), producing a fault situation in which a cable slacks or the end effector is jolted out of position by an undesired force or torque.

On the other hand, if λ moves too quickly through the null space, rapid changes in the tension distribution can lead to undesired vibrations. Based on available experimental evidences, it is chosen to set the rate of change of λ from one set point to the next to at least the speed of the velocity of the wrench variation. In the results, the speed discussed is the same of the velocity of variation of the wrench from the static situation to the situation where the maximum wrench is exerted.

Each polygon Ω_i is related with a corresponding value of W so, when the trajectory planning goes from the corresponding λ_i^* to λ_{i+1}^* , which belongs to the following polygon Ω_{i+1} , the tension planner follows some sample points, λ_i , that are obtained from the straight line which links λ_i^* with λ_{i+1}^* . However, the sample points λ_i don't have a clear associated value of W because they are taken directly from the nullspace geometry to make an agile process. The desired tensions corresponding to each point in the null space are calculated with two different methods, depending on the speed needed in the execution of the task:

1. Method I: Fixed set-point wrench:

The tensions can be calculated quickly by imposing the same values of the wrench (W) to all sample points λ_i from the optimum point λ_i^* to the following optimum point λ_{i+1}^* , corresponding to the sample points along the entire trajectory between the set points, being λ_i^* the optimum point of the region Ω_i that correspond to that W . This method situates the trajectory of λ entirely within the corresponding polygon of feasible tensions. However, tensions will change very abruptly when each set point is reached. This fast method can lead to high vibrations and dynamic effects because the wrench changes only at the set points instead of varying in each sample of λ .

2. Method II: Proportional wrench variation along trajectory:

More-secure approach implements Eq. (12) by taking multiple values of W between the optimum points λ_i^* . The value of W for each λ_i is obtained by increasing its value from the initial value to the value that has the following optimum point, λ_{i+1}^* . This increment of the value of W is defined as proportional to the length covered by the tension planner between the previous and the following optimum points (λ_i^* and λ_{i+1}^*).

The advantage of this tension planner in comparison with the common method is that it is not necessary to calculate the polygon of feasible forces for each value of λ_i considered because it is guaranteed that λ_i is inside one of the polygons of feasible tensions. The other advantage is that W for each λ_i point is not calculated by using the polygon of feasible tensions.

It is not analyzed what is the more secure tension distribution (Borgstrom et al., 2009) for each λ_i point but what is the more secure tension distribution considering all the sample points.

2.8. Theoretical results

The system to be analyzed is a cable-driven suspended robot with size of 10 m in length, 5 m wide, and 6 m in height. The end effector is a cube 1 m on a side with $n = 6$ degrees of freedom and is actuated by $m = 8$ cables, so that the degree of redundancy is $m - n = r = 2$. The analytical and numerically simulated results were obtained by considering that gravitational force as the external wrench applied to the platform, however, the position of its center of mass was also varied to test the validity of equation (2.7). The minimum cable tension was set to 0 N.

Figure 2.8 Dimensions and connection anchors of the suspended parallel manipulator analyzed with analytical and simulated results. The end effector is a cube 1 m on a side.

2.8.1. Maximum wrenches:

The maximum resultant wrench of the end effector is calculated for each one of its five degrees of freedom. The vertical axis is not considered for the reasons already discussed before. When calculating the tension distribution (λ_{opt}^F) needed to produce a maximum effort (W_{max}), the final tension distribution must be generated such that it remains inside the polygon of feasible tensions. Results are obtained for the four different positions of the geometric center of the end effector O' : A = (5, 2.5, 0.5) m; B = (9, 4, 0.5) m; C = (9, 4, 2.5) m; D = (5, 2.5, 2.5) m.

The position of the center of mass is defined by the position $p_{GA} = (0,0,0)^T$ m and $p_{GB} = (-0.25, -0.1, -0.25)^T$ m. The mass is 150 kg. The results obtained from each of these calculations, excepting the vertical linear axis because of Eq. (2.34), are listed in tables 1 to 4.

The boundaries for the forces and torques applied at the end effector were established using the theoretical method discussed above. The wrenches applied for four different positions of the effector were also analyzed. However, the maximum forces and torques are also analyzed along the Wrench Closure Workspace (WCW) to have a clearer view of the limits on the wrenches over all the workspace of the robot.

Table 5 lists the time needed to produce the maximum and minimum wrench component in each of the five dimensions by using the proposed method. The results of this computation are the value of the wrench and the values of the tensions in the m cables. Computation was performed with an Intel® Xeon® X5570 processor @ [2.93GHz, 2.93GHz].

Table 2.1 Maximum and minimum wrench of end effector in $A = [5, 2.5, 0.5 \mid 0, 0, 0]$ (m|rad)

	$FX(kN)$	$FY(kN)$	$TX(kN-m)$	$TY(kN-m)$	$TZ(kN-m)$
$p_{GA} = [0, 0, 0]$	1.336	0.668	0.936	0.952	1.102
	-1.336	-0.668	-0.936	-0.952	-0.918
$p_{GB} = [-0.25, -0.1, -0.25]$	0.962	0.558	0.635	1.047	0.744
	-0.902	-0.477	-0.832	-0.856	-0.656

Table 2.2 Maximum and minimum wrench of end effector in $B = [9, 4, 0.5 \mid 0, 0, 0]$ (m|rad)

	$FX(kN)$	$FY(kN)$	$TX(kN-m)$	$TY(kN-m)$	$TZ(kN-m)$
$p_{GA} = [0, 0, 0]$	0.267	0.267	0.446	0.428	0.276
	-2.405	-1.069	-0.371	-0.356	-0.230
$p_{GB} = [-0.25, -0.1, -0.25]$	0.009	0.044	0.807	0.388	0.046
	-1.731	-0.944	-0.159	-0.424	-0.009

Table 2.3 Maximum and minimum wrench of end effector in $C = [9, 4, 2.5 \mid 0, 0, 0]$ (m|rad)

	$FX(kN)$	$FY(kN)$	$TX(kN-m)$	$TY(kN-m)$	$TZ(kN-m)$
$p_{GA} = [0, 0, 0]$	0.42	0.42	0.612	0.526	0.421
	-3.78	-1.68	-0.459	-0.395	-0.316
$p_{GB} = [-0.25, -0.1, -0.25]$	0.023	0.169	0.444	0.4	0.17
	-2.673	-1.618	-0.173	-0.435	-0.029

Table 2.4 Maximum and minimum wrench of end effector in $D = [5, 2.5, 0.5 \mid 0, 0, 0]$ (m|rad)

	$FX(kN)$	$FY(kN)$	$TX(kN-m)$	$TY(kN-m)$	$TZ(kN-m)$
$p_{GA} = [0, 0, 0]$	2.1	1.05	0.912	1.299	1.838
	-2.1	-1.05	-0.912	-1.299	-1.378
$p_{GB} = [-0.25, -0.1, -0.25]$	1.543	0.997	0.718	1.457	1.311
	-1.499	-0.881	-1.102	-1.141	-1.013

Table 2.5 Time required for obtaining maximum efforts for position $B = [9, 4, 0.5 \mid 0, 0, 0]$ (m|rad)

	$FX(ms)$	$FY(ms)$	$TX(ms)$	$TY(ms)$	$TZ(ms)$
$p_{GA} = [0, 0, 0]$	23.77	22.50	21.56	19.61	20.00
	22.06	21.58	20.96	21.32	21.35

2.8.2. Region of maximum wrenches:

Another result that can be obtained with this analysis is the maximum external force or torque along one specific axis when the end-effector is situated in different regions of the workspace, as shown in Fig. 2.9. This force/torque is applied in positive axis X and Y when the effect of the weight is totally compensated. It can be observed in a) and b) respectively. A higher value of F_x (or F_y) could provoke losing a cable tension or undesirable forces in the vertical axis. Fig. 2.10A and 2.10B represent the maximum external torque in x and z axis, respectively in each point of the workspace. This knowledge is useful to select those regions where is better to situate the end-effector to exert a high value of force/torque. In addition, these values allow a better sizing of maximum tension of cables in order to achieve desired effort in the end-effector.

Figure 2.9. The maximum force of the end-effector in each region of the workspace. A) Maximum force in x-axis. B) Maximum force in y-axis

Figure 2.10. The maximum torque of the end-effector in each region of the workspace. A) Maximum torque in x-axis. B) Maximum torque in z-axis

2.8.3. Nullspace path planning

Maximum and minimum wrenches of table 2.2 ($\mathbf{B} = [9, 4, 0.5, 0, 0, 0]$ and $\mathbf{pG} = [0, 0, 0]$), are obtained by setting in the null space the value of λ_{opt}^F defined in Eq. (34). The maximum and minimum wrench component in each dimension is shown in Fig. 2.11. The boundary of feasible values for the initial applied wrench, $\mathbf{W}_0 = [0, 0, -m \cdot g, 0, 0, 0]$, is also included (Ω_0). This initial wrench is the vertical force that the cable tensions need to apply to balance the weight of the platform. The same initial wrench can also be applied by initializing the λ value in any point of this polygon of feasible tension distributions.

Since applications that require the system's maximum force and torque output usually require it quickly, the analysis aims to plan a path that reaches each of the maximum and minimum wrenches quickly with short computation time. As Fig. 2.11 shows, several maximum and minimum wrenches have their optimum null-space positions inside the initial polygon of feasible tensions. In these cases, the maximum wrench can be produced simply by setting the λ value in the position required by the final tension configuration. In this case, the whole process from the initial value to the maximum wrench can be completed with the same value of λ .

In this example, some wrenches require a λ value that lies outside the initial polygon of feasible tensions (Ω_0). Those wrenches are $+T_x$, $(-F_y)$ and $(-F_x)$. With those wrenches with corresponding λ_{opt}^F outside the initial feasible polygon, one cannot directly determine if any value of λ is common to both feasible configurations, so the method introduced in section 5 must be applied.

Figure 2.11. Values of λ_{opt}^F needed to exert the corresponding maximum wrench when the end-effector is situated in $\mathbf{B} = [9, 4, 0.5, 0, 0, 0]$ m. The region of valid tension configurations, Ω_0 , is defined for $\mathbf{W}_0 = [0, 0, -m \cdot g, 0, 0, 0]$

In Fig. 2.11, the black polygon marks the region of λ values that provide a feasible tension distribution that balances the weight of the effector appropriately. If an extreme force or torque is desired in one axis, the corresponding λ_{opt}^F value needs to be calculated. The polygon allows only some configurations while other

configurations $(T_x, -F_x, +T_y)$ do not allow the manipulator to reach the optimal null-space configuration directly from the equilibrium state.

These extreme points can be obtained by increasing the value of the desired force, which modifies and translates the shape of the constraint polygon. This progressive modification begins with the initial polygon and ends with the polygon of the final desired wrench.

Fig. 2.12 illustrates the displacement in the null space needed to reach the maximum value of $(-F_x)$ from the equilibrium state when the end effector is fixed in point B. As seen in table 2.2, the maximum force is -2405.5 N. Following the method shown in section 2.5, five regions of valid tension configuration have been obtained $(\Omega_0, \Omega_1, \Omega_2, \Omega_3, \Omega_F)$ and six optimum points $(\lambda_{opt}^0, \lambda_1^*, \lambda_2^*, \lambda_3^*, \lambda_4^*, \lambda_{opt}^F)$ to exert the force $(-F_x)$, from 0 to -2405.5 N. As it can be seen, the region of feasible tension configuration changes its size and it displaces towards the end point, λ_{opt}^F that corresponds to point F. According to (Bouchard et al., 2010), those regions are zonotopes so they have their sides parallel to each other.

Figure 2.12. Trajectory in nullspace of λ with the fixed position of the end-effector of Fig. 10 with wrench values that go from $F_x = 0$ (Equilibrium state) to $F_x = -2.4055$ KN, which is the maximum value of force in the x-axis in opposite direction (as seen in table 2). $(\Omega_0, \Omega_1, \Omega_2, \Omega_3, \Omega_F)$ are the polygons of feasible tension distribution for each one of the optimum points $(\lambda_{opt}^0, \lambda_1^*, \lambda_2^*, \lambda_3^*, \lambda_4^*, \lambda_{opt}^F)$. The F_x values chosen for the optimum values are: $F_{x1} = 0N$, $F_{x2} = -600N$, $F_{x3} = -1200N$, $F_{x4} = -1800N$, $F_{x5} = -2400N$. Black dots are sample points λ_i to go from one optimum point to the following, 10 samples are chosen between optimum points.

Once the optimum points $(\lambda_{opt}^0, \lambda_1^*, \lambda_2^*, \lambda_3^*, \lambda_4^*, \lambda_{opt}^F)$ are obtained by using scheme of fig. 2.7, it is needed to choose the sample points, λ_i , between adjacent optimum points. In this example, 10 sample points are set for each trajectory section between two optimal points.

The point λ_{opt}^0 is situated in the center of Ω_0 . The next point, λ_1^* , is situated in the center of the polygon defined by the intersection of the polygons Ω_0 and Ω_1 . The points λ_2^* and λ_3^* are the intersection points of Ω_1 and Ω_2 the first one and between Ω_2 and Ω_3 the second one. The point λ_4^* is the center of the polygon Ω_3 because there is no intersection between it and the following polygon. The last set point is λ_{opt}^F , situated in the center of the very small polygon of feasible tension (Ω_F) of this maximum wrench, $W_{max} = F_{x5}$.

As it can be seen, the polygon of feasible tensions of the last point is very small because there are not many tension configurations that can provide that maximum wrench. In addition, the maximum force considered is $-2400N$ and not the real maximum value $-2405.5N$ in order to make the example clearer. If the maximum point is chosen, the polygon of feasible tension uses to be a single point instead of a polygon.

For each one of the optimum points, it has been obtained the desired tension for each cable, τ . In Fig. 2.13A, the method I of “Fixed set-point wrench” is used. As it can be observed, a step appears when there is a change in the value of W . The λ value, however, continue moving along the tension planning.

Figure 2.13. Tension values for each cable obtained by using A) the method I: “Fixed set-point wrench”. B) The method II: “Proportional wrench variation along trajectory” and C) The usual method described in section 3 that analyze each sample point.

In Fig. 2.13B, the tensions were calculated using varying wrenches along the trajectory. In this way, the values of $\mathbf{W}$ are increased gradually as the λ point advances along the trajectory. That figure shows that this algorithm produces smoother motion with very little cost to the computation time.

For comparison, Fig. 2.13C shows the results calculated with the conventional method previously discussed. That method analyzes all the sample points between the initial tension configuration and the final configuration. For each point, the algorithm calculates the polygon of feasible tensions to check that λ point produces a feasible tension configuration. In addition, it sets a safe configuration far from the boundaries of the polygons. This method is safer and provides smooth variations in the tensions, but every sample needs to be analyzed. The results in Fig. 13.c are similar to those obtained with the faster proposed method.

The computation time needed for each of the three methods is shown in table 6. The three path planners were generated on an Intel® Core™ i7-4710HQ processor @2.50 GHz. The results show that for only 10 samples, the proposed method is a 67% faster than the usual method described previously. When taking 1000 samples for a smooth transition in tensions, the proposed method is almost 12 times faster than the usual method for planning paths for which the desired wrench requires a final null-space position outside the initial polygon of feasible tensions.

Table 2.6 Time required for each method of the nullspace path planning

Samples	Method I (s)	Method II (s)	Usual method (s)
10 samples	0.73	0.74	1.24
100 samples	0.84	0.91	2.45
1000 samples	1.03	1.42	15.83

2.9. Simulated results

2.9.1. Maximum wrenches

Simulations of the cable robot were implemented in the multibody dynamic simulation software MSC ADAMS. The end effector and the frame structure were modeled as rigid solids. The cables were implemented as linear springs with diameter of 4 mm with negligible mass. The cables were attached to winches situated at the base of each pillar. Those cables pass over pulleys situated on top of the pillars at 6-meter height, and their ends are fixed to specific points of the effector with the configuration shown in Fig. 2.8.

The objective of the simulation is to set a given force or torque at the end effector. The target wrench is increased from zero to a high value to find the value at which a vertical force appears due to the constraints on the suspended robot.

The tension in cables is calculated using (2.11) to generate the target wrench at the end effector. The valid point of the null space of A is calculated by using the vertex computation. In those cases where the wrench become so extreme that no feasible point in the null space is available the latest valid point of the null space is taken.

Figs. 2.14-17 shows the simulation results. The end effector is resting on the ground at $A = [5, 2.5, 0.5, 0, 0, 0]$ m, with all linear and angular movement blocked. The first 0.5 seconds of the simulation correspond to pre-tensioning of the cables to approach the desired resultant wrench, W_R , at the end effector. Once this point is reached, the force is increased gradually. The two other resultant linear forces and three resultant torques are set to zero. Fig. 2.14 consider an increasing positive force, the first with the center of mass at $p_{GB} = (0,0,0)$ m and the second with the center of mass at $p_{GB} = (-0.25, -0.1, -0.25)$ m. Fig. 2.15 considers an increasing negative force Y , with the same difference in the center of mass.

Figure 2.14. Values of resultant forces in the end-effector when an increasing force in axis Y is applied. It can be seen how an upward vertical force appears when the maximum applied force is reached. (a) Positive force in Y axis with balanced center of mass. (b) Negative force in Y axis with balanced center of mass.

Figure 2.15. Values of resultant forces in the end-effector when an increasing force in axis Y is applied. A) Positive force with unbalanced center of mass. B) Negative force with unbalanced center of mass.

The limits on the linear forces that a suspended cable robot can apply are apparent. When this limit is reached, wrenches that should be constant change suddenly. The results simulated in MSC ADAMS coincide with analytical calculations of the forces in the y -axis. This means that when the maximum allowable value of force in y -axis is achieved, an upward vertical force appears (green line in Figs. 2.14-15) and the horizontal force in the Y direction decreases. When this frontier is exceeded, no valid λ is available, so the value of λ_{opt}^* is maintained. The behavior beyond this frontier is uncertain and severe vibration appeared in some of the simulations.

Fig 16-17 shows the results when an increasing torque is applied in the Z -axis with the end effector fixed at $A = [5, 2.5, 0.5, 0, 0, 0]$ m. In fig. 2.16, the center of mass is at p_{GA} . Fig. 2.17 shows the case with the center of

mass at $\mathbf{p}_{GB}$. When the torque is higher than the torque limit, the resultant wrenches cannot maintain their reference values and they begin to increase or decrease. Vibrations appear when the null space collapses. A sudden upward vertical force appears in the lower graphs of figs. 2.16-17, and they coincide with the modification of the tendency of torque values.

Figure 2.16. Values of resultant Torques in the end-effector when an increasing torque in axis Z is applied (upper graphs). It can be seen how an upward vertical force appears (lower graphs) when the maximum applied torque is reached. This case corresponds to a positive torque in Z axis with balanced center of mass.

Figure 2.17. Values of resultant Torques in the end-effector when an increasing torque in axis Z is applied (upper graphs). It can be seen how an upward vertical force appears (lower graphs) when the maximum applied torque is reached. This case corresponds to a positive torque in Z axis with unbalanced center of mass.

The small error between the experiment and the theoretical values is explained by the small variation in cable tension due to the vibration of cables when high tension is applied.

2.9.2. Tension planning

The three proposed methods are tested in this section to check the behavior of the forces exerted by the end effector when the proposed online tension plan is executed. This test plans tension distributions to exert the maximum force in the x-axis, since this force requires a plan that goes outside of polygons of feasible tensions. The simulations of the three different tension planners in MSC ADAMS reveal the dynamic behavior of the robot when it is in unstable configurations. For this test, the effector was fixed in the position $B = [9, 4, 0.5, 0, 0, 0]$ m and the three proposed methods are applied to impose the cable tension, τ .

The maximum force in the x-axis is set to 2200 N instead of the theoretical maximum force of 2405.5 N because the vibrations caused at the theoretical could generate forces at the end effector that take it outside the corresponding feasible region (Ω).

The end effector was fixed in position and the tensions obtained in Fig. 2.13 were imposed on the fly, so that the velocity for processing the desired tension values determines how quickly the wrenches at the platform change.

Simulations of motions planned with method I: “Fixed set-point wrench” shown in Fig. 2.13A, provided unstable solutions with very high vibrations. This means that method I is not viable for common applications.

Results obtained by imposing the tension values calculated by the method II: “Proportional wrench variation along trajectory”, shown in Fig. 2.13B, are shown in Fig. 2.18. The response is faster with fewer samples, but the system has higher vibrations.

If the tension distribution is planned using the common method, each sample in the null space needs to be analyzed and checked against the value of the wrench imposed at the end effector. This method is the most secure because there is no uncertainty in the wrench value imposed. However, this usual method analyzes the polygon of feasible tension distribution for the given end effector wrench and calculates one optimum point in the null space for each value of wrench. This calculus requires more computation time, as shown in Fig. 2.19.

Figure 2.18. Linear forces exerted by the end effector situated at B with the tension planner of method II applied to produce $F_X = 2200$ N. The black line is the force in X-axis, the red line is the force in Y-axis, and the blue line is the force in Z-axis. a) With 10 samples the needed time is 0.74 s. b) With 100 samples, the needed time is 0.91 s. c) With 1000 samples, the needed time is 1.42 s.

Figure 2.19. Linear forces exerted by the end effector situated at B when applying the tension planner of method III to produce $F_X = 2200$ N. The black line shows the force in the X-axis, red line is force in the Y-axis and the blue line is the force in the Z-axis. a) With 10 samples the needed time is 1.24 s. b) With 100 samples the needed time is 2.45 s. c) With 1000 samples the needed time is 15.83 s

As it can be observed in table 7, the force values in the Y and Z axes, which are the axes that are pretended to maintain with a fixed value of 0N. The deviation values of these forces respect the desired value doesn't show a relevant increasing of the error for the method II respect the common method.

Seeing that the behavior of the common method and the method II are similar, the only noticeable difference between both methods is the velocity of calculating the tension planner, being the method II faster than the common method, as it is shown in table 6.

Table 2.7 Mean and standard deviation of the linear force applied on Y and Z axes

		Samples	FY(N)	FZ(N)
	Mean			
Metod II		10	2.35	6.98
		100	2.19	4.51
		1000	1.58	-2.50
	Std. Dev.	10	103.4	418.4
		100	101.4	325.5
		1000	65.43	79.12
Common method	Mean	10	23.24	1.90
		100	1.85	7.37
		1000	1.91	8.73
	Std. Dev.	10	1724	952
		100	108.6	258.9
		1000	15.1	32.59

2.10. Discussion

Several conclusions can be drawn from the results presented above. The maximum desired cable tension can be calculated from the weight of the end effector, before defining the cable tension attending to its properties and the actuator characteristics. This is due to the constant gravity force that must compensate for the sum of the vertical tension components in all the cables, which could serve as a first step in the selection of materials and motors for the CDPR. The knowledge of this specific boundary for suspended CDPR helps in the sizing of the end effector weight as well as the maximum wrenches that can be applied. Due to the importance of the effector's weight to counteract tension forces, in some cases, it could be necessary to consider the use of heavier end effectors if the wrench necessary for a desired task does not have a valid polygon of feasible tensions.

This calculation also yields the regions of the workspace from which strong forces and tensions can be exerted. Stronger forces and wrenches can be performed in the upper regions of the workspace if the cable tension is not bounded during the planning process because the vertical component of the tension in each cable will be small enough to be balanced by the gravity force in this case.

The optimal region of the workspace in which strong wrenches can be exerted is also revealed by the analysis above. For example, the maximum linear force can be produced by situating the end effector on the side opposite from the direction of the desired force. For example, if a large force in the positive x-axis is desired, the end effector, generally, should be situated in a region with low x coordinates. The cables that are pulling the high tensions will be oriented almost horizontally in this position, so that the vertical component of the tension is easily balanced by the weight of the end effector. Knowing this, a lighter end-effector could be used to exert high wrenches if it is working in the areas where these feasible wrenches have greater values.

It also has been demonstrated the importance of using the null space basis to find the optimal tension distribution of redundant cables when applying large-magnitude wrenches. With the polygon of feasible null-space values in hand, the tension configuration can be set far from the fault condition. Normally, the null-space points for different trajectories and wrenches are planned to remain inside the polygon of feasible tension of the initial configuration. However, when exerting large wrenches at specific positions, the desired tension configuration may drive the robot into a null-space position outside the initial polygon of feasible tensions. In that situation, the path through the null space needed to reach the end condition isn't known a priori.

In case that the working point is outside the polygon of feasible tensions, motion planners typically ensure that the null-space point is in a secure location, far from regions of unfeasible tension distributions. Though this conventional method is fast when planning motion for a single point, if many points must be analyzed from the initial to the final configuration, the conventional approach won't be fast enough for developing fast tasks that require to analyze data from other external sources.

The proposed method reduces the time required for the tension configurations that drive null-space points outside the initial polygon of feasible tensions. This situation usually arises when large wrenches are exerted while the end effector is in certain positions. By reducing the time needed safely exert effort from such positions, a cable-driven robot could be designed for tasks that require rapid and strong forces or wrenches like pressing or drilling.

The spring elasticity also allows to solve the forward kinematics providing as many equations as unknowns, as presented in (Jean-Pierre Merlet, 2014). The actual cable tension is very sensitive to stiffness uncertainty so this influence is reduced by adding springs whose stiffness has been previously measured in different conditions.

The proposed method allows to set the minimum number of points for analyzing the tension distribution when the end-effector is fixed in its position. If platform trajectories are considered the conditions and proofs of continuity for end-effector movement are shown in (Verhoeven, 2004).

The results and know-how obtained in the analysis performed in this chapter allows to define the maximum wrenches that can be exerted to the robot where the underwater simulation is applied. Helping to define if the required underwater forces could be applied in each region of the workspace. The soft and fast path planner also allows to provide a simulation of higher quality avoiding delays due to the computing time and also reducing the cases where the any cable could get into a fault condition. In the following chapter, a novel application for this nullspace tension planner is devel

3. PASSIVE RECONFIGURATION BASED ON COMPLIANT ACTUATION

3.1.- Introduction

As observed in chapter 2, one of the advantages of the actuator redundancy is the possibility to control more than one action or fulfil secondary objectives as performed in (Flacco et al., 2015). CDPR usually have this redundant constraint to compensate their inability to push a load with cables or to increase their workspace in a safe way. Taking advantage of this feature, additional tasks can be applied to the end-effector to improve the quality of the underwater simulation. Those additional tasks could be related with the application of underwater wrenches to different parts of the body whose immersion is being simulated on ground. In this way, forces exerted by the redundant actuators could be applied to end-effectors composed by more than one rigid body or even to bodies that could require more than one point of application of the force spreading them in a more distributed pattern. CDPRs with passive reconfigurable platform are parallel robots whose end-effector is a passive mechanism instead of a rigid body that is intended to be controlled by using the actuator redundancy and specific design of cable configurations.

A special cable configuration is proposed to act on two different bodies from the platform while they are being pulling by one single actuator. This type of cable configuration can be used in CDPR with a reconfigurable end effector in order to use one degree of actuation over the inner one degree of freedom of a reconfigurable platform. This configuration could be useful when one or several degrees of actuation are intended to be applied to the internal motion of a passive reconfigurable end-effector. It can be used in any CDPR in whose end effector it is desired to add additional degrees of freedom that want to be controlled by using the current degree of actuation.

For instance, one robot with eight degrees of actuation with an end effector with seven degrees of freedom (six DOF corresponding to one rigid body and one DOF corresponding to the joint of the first body with a second body), could be controlled by attaching some cables to one body and the rest of the cables to the second body. This method cannot control the six DOF of each one of the two bodies but just the seven DOF of the whole reconfigurable end effector. This method, already proposed in (Barbazza, Zanotto, et al., 2017) and built in 2 dimensions in (Jadhao et al., 2018) is interesting because it can exert an equivalent quantity of effort to both bodies of the platform.

One schematic example of the proposed concept is explained in Fig. 3.1, where a planar suspended CDPR with reconfigurable end effector is actuated by using four cables actuated independently. The second body can just slide along the first body. Two of the cables aim to control two DoF of the first body while the other two cables provide their actuation effect to the second end effector. As each body has three DoF in the planar case, they are under actuated when they are considered as independent bodies. The entire platform, which is composed by the two bodies had four degrees of freedom (three DoF of one rigid body and one DoF of the available movement of the second body) and four degrees of actuation, being $m = n$. With the configuration from the figure 3.1, where each body has two cables attached, the movements of the entire platform are very influenced by the internal movement between the two bodies, making difficult to control the global end-effector. In the example of Figure 3.1, a torque in the x-axis (T_x) is desired for the entire end effector; however, an internal force between the two bodies appears because the cable that is attached to B_4 has to exert high tension to impose the desired torque T_x .

Figure 3.1. Schematic description of a planar suspended CDPR with reconfigurable end effector actuated by simple cables. It is seen that when a torque is imposed on the entire end effector, it appears as an internal force in the second body of the end effector, making the control of all DoF of one of the bodies difficult.

In this chapter 3, a mechanical device and a method for controlling all the degrees of freedom of one body is proposed while the second body is controlled as a secondary task when the first body is totally controlled. This method is based on the use of one cable able to exert its actuation effort to the two bodies of the end effector at the same time while being actuated by one single motor. As seen in Fig. 3.2A, if the elasticity of the cables is neglected by attaching the two branches of this special actuator directly to both end effectors, it is only possible to exert tension to one body and its corresponding defined tension value to the other body, that cannot be independently controlled because it doesn't have the DoF provided by the elasticity. In Fig. 3.2B, the proposed method for controlling all the degrees of freedom of the first body of the end effector without the influence of the internal degrees of freedom of the reconfigurable platform is shown. In this way, the second body of the end effector can be controlled with more or less priority with respect to the control of the first body. For instance, if the first body has high priority on its control, the cable that acts on the second body can be tensed with the values allowed by the tension distribution needed by the first body, where the tension boundaries can be set at the value of τ_A . However, if the second body needs high priority, it is set at the desired tension value of τ_B without considering whether the cables can provide an appropriate tension distribution in the first body.

This special cable configuration requires the tension and elongation to be considered at the same time, so this, an appropriate sensor system is needed to acquire both signals at the same time to solve the geometrostatics problem of the whole robot. The sensor system proposed is based on a linear position encoder that is able to detect the elongation of the spring of the cable. In this way, by knowing the stiffness of this spring, it is possible to measure the elongation of the first branch of the cable directly and the tension imposed on the first body by the cable in an indirect way (J. P. Merlet, 2017).

Cable tension has to be considered to solve the redundancy of the system. For this reason, the additional sensor can provide the current tension value that the cable is imposing to the main body of the platform. The added springs also can help to obtain more accurate measures of the spring elongation. Knowing a priori the stiffness of the springs, the tension that is being applied to the first body by the compliant actuator can be obtained by applying Hooke's Law. The springs requires an elastic model of the system.

Figure 3.2. A) Example of a cable acting on the two bodies of the end effector directly. In this case, the first body can be controlled in its three DoF by using the four actuated cables. However, if the cable is not elastic, the second body cannot have its movement controlled as it is dependent on the position of the first body; B) Example of a cable acting on the two bodies of the end effector. The elongation of the first branch of the cable can be modified by using a spring with stiffness k_1 . In this way, the relative position of the second body with respect to the first one can be controlled with the tension τ_2 . The value of τ_A depends on the position desired for the second body but is compensated by the three cables that can act on the first end effector in order to have control of the three DoF of the first body and the control of the relative position of the second body.

This special cable configuration, seen in figure 3.2B, could be related with compliant actuators due to the inner elasticity provided by the spring and the soft behavior of the cables in not constraint directions that allow the mechanism to deviate from its equilibrium position. The cable corresponding to the compliant mechanism parts from a winch situated in the upper side of the robot and is split into two different cables. One of these split cables is directly attached to the second body of the reconfigurable platform while the other is attached to a spring. This spring connects the terminal of the cable with the first body of the platform. This last side of the compliant actuator with the spring is sensorized by using a linear transducer to measure the length of that spring. This sensor is fixed to the body and its thread goes through the inside of the spring that attaches to the cable. In this way, the length can be directly measured and the tension of the spring can be obtained through indirect measurements by knowing the stiffness value of the spring and the transducer thread.

The main advantage of the use of compliant actuators in this prototype is the possibility of controlling the main end effector with all the actuated cables maintaining all its wrench capability. The second body DOF control can be done by using only one branch of this special cable. With this method, the first end-effector can maintain its full controllability while the reconfigurable mechanism can be controlled in those states where the redundancy provides a wide range of tension distributions. This property is useful if the second body acts as a manipulator that is only actuated on certain occasions while the main end effector can have all its capabilities the rest of the time.

The length value imposed by the corresponding motor of the controlled part of this compliant actuator is also used to control the internal DoF of the platform by exerting effort in both bodies of the platform. Redundant constraint of the system can compensate the perturbation added by this compliant mechanism by considering tension value provided by the sensorized part as the cable tension of a common CDPR. With this cable mechanism, it is possible to control one degree of freedom while the rest of the cables compensate the perturbation added by its tension. Due to the modularity of this compliant actuation mechanism, it should be possible to use this mechanism for developing CDPR with reconfigurable platforms of more than one degree of freedom by using as many compliant actuators as the DoF of the platform. The resolution of the kinetostatics of this compliant mechanism could be related with the Forward Kinematics (FK) of under-constrained CDPR.

As it can be seen in figure 3.2B, the sensorized spring measures the force applied to the first body by the compliant actuator and elongation of this spring with an accuracy related with the sensor quality. However, the position and force in the compliant actuator remain coupled due to the relation between the cable tension and their elongation. This means that, for each geometric configuration of the compliant actuator there will be a specific set of forces that maintain the force closure, imposing a specific elongation in each cable. For this analysis, it is needed to take in account the stiffness of the cables and the forces applied in each of them in order to consider this elongation in the geometric model.

Due to this relation between geometry and forces, both analyses are performed in each time sample from the path planning of the movement. The geometrico-static problem imposes a double relation between geometry and cable forces: in one hand, it is needed to close the force loop considering the linear elongation while in the other hand those forces need to be applied in the line of the cable because their axes lines are the only direction they can exert wrenches. Due to the geometry of this mechanism, an iterative model can be used to achieve the force equilibrium in the compliant mechanism considering the information given by the sensorized spring: One iteration calculates the geometry without considering elasticity (geometric resolution) while the wrenches are analyzed in the second part of the iteration considering the stiffness of the cables and the direction of the forces (wrench resolution). The next iteration cycle obtains the geometric position considering the previous equilibrium of forces and elongations. In those experiments, a kinetostatic analysis is performed and the speed of the movement of the system is low enough to have time to solve this iteration problem.

To test the performance of this cable-driven mechanism with reconfigurable end effector, a small-scale prototype is developed to analyze the behavior of the compliant actuator controlling the inner DoF of the platform. These results could justify the use of this mechanical system in big scale CDPRs to perform more realistic and accurate simulations to articulated or deformable end-effectors, very useful in the case of this related project where the underwater wrenches are desired to be imposed in an articulated end-effector. When simulating humans or humanoids in the CDPR, the EE_1 could provide six DoF in the trunk of the robot while the additional DoF can provide dynamics in its hips to simulate underwater torque in a more accurate way. With the use of the compliant actuator, all of the actuators are situated far from the humanoid to reduce risks.

Other applications that could be used with this kind of compliant actuator include grasping large and irregular objects in very large workspaces by using the advantage of the cables instead of rigid links in the robot structure. Furthermore, the compliant behavior of these actuators could allow for this kind of robot to direct human-robot interaction.

3.2.- Related Work

Redundantly constrained parallel robots were analyzed in (F. Gosselin & Lallemant, 2001)(Mohamed & Gosselin, 2005), their workspace in (Ghasemi et al., 2009) and the possibility of handling secondary tasks with the redundant actuators appears in (Siciliano & Slotine, 1991)(Flacco et al., 2015). In (Lamaury & Gouttefarde, 2013b)(M Gouttefarde et al., 2015), an agile algorithm is presented to set the geometric region that defines all feasible tension distributions. One commonly used tension configuration comes from the minimization of cable tension by using the Moore-Penrose Pseudoinverse (Barata & Hussein, 2012). This kind of optimization has the risk of providing negative tension values that are not feasible for CDPR, so in (Borgstrom et al., 2009) it was described the use of a condition that provides a safe tension distribution, far from faulty regions.

In (P. Lambert & Herder, 2016), fundamental aspects of general parallel robots with a configurable platform are described. In (Mohamed & Gosselin, 2005), a generalized analysis of this kind of robot was performed by using screws algebra considering the EE as a close-loop chain. In (Jadhao et al., 2018), the first known prototype of cable-driven robot with reconfigurable end effector was presented (according to the literature analyzed). This was a planar haptic device with four DoF that provided planar motion. In that study, a geometric and static analysis was developed. In (Barbazza, Zanutto, et al., 2017), an optimized shape for the reconfigurable end effector for cable-driven suspended robots was proposed with the objective of avoiding obstacles situated on the ground. Some applications of the reconfigured platforms include grasping objects of irregular shape or large volume like the first reconfigurable platform robot presented in (B. J. Yi et al., 2002), micro-positioning and haptic devices (Mohamed & Gosselin, 2005), or end effectors able to avoid singular postures within their workspace (Pierrot et al., 2009). In (Nguyen et al., 2014) a reconfiguration where the winches move along bridge cranes is proposed to increase the workspace.

The first robot with a reconfigurable end effector appeared in 2002 (B. J. Yi et al., 2002), the first design of a robot with this configuration that was actuated by tensed cables appeared in 2017 (Barbazza, Zanutto, et al., 2017). Until now, only two references have been found in the literature regarding this last type of cable robot (Jadhao et al., 2018)(Barbazza, Zanutto, et al., 2017). Considering the field of this novel configuration, the main contribution of this chapter is the consideration of a special cable mechanism, denominated compliant actuator, that can exert force in two different bodies of the reconfigurable end effector.

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Figure 3.3. Jadhao's haptic prototype with two end-effectors for two fingers. A) Scheme of its 4 DoF and 6 actuators. B) Actual prototype. From (Jadhao et al., 2018)

By controlling the first body of the end effector, it is possible to apply the well-known control algorithms intended for CDPR with rigid bodies without the perturbation of the internal movement of the platform like in (Kiani & Mashhadi, 2017)(Hamed Jamshidifar et al., 2018) (Mottola et al., 2018)(Jiang et al., 2018). However, as seen in Figure 3.2B, an elastic component needs to be added to the first branch of the cable in order to have an elongation that imposes a motion in the second body. Due to this elongation, an elastic analysis of the cables and springs must be performed. Also the direction where the tension is being exerted to the first body needs to be calculated as well as its value by performing a geometro-static analysis of the under constrained compliant mechanism.

Figure 3.4. Barbazza's reconfigurable CDPR proposal. From (Barbazza, Zanotto, et al., 2017)

Linear sensors have been already used to solve the direct kinetostatics problem in cable driven parallel robots like that in (J. P. Merlet, 2017) and in rigid links parallel robots as seen in (Bonev et al., 2001). The use of this linear sensor combined with a spring can provide a measurement of length and tension in one of the branches of the compliant actuators when the spring is modeled with accuracy. This way of measuring provides the necessary information to solve both problems: kinetostatic and tension configuration.

In (Featherstone, 2006), a kinestostatic analysis was made to a spatial mechanism of rigid links defined as tensegrity-based with compliant connectors. It had seven actuators and six DoF. In (Moon et al., 2013) the internal energy value is established for the springs to constrain the $r = 1$ redundant degree of freedom. In this article, redundant DoF were not constrained by energy assumptions like in (Sala et al., 2004), but by the tension of one specific cable related to its linear deformation. This length variation due to cable tension was amplified by using springs with less stiffness than the cable. Those springs were situated in serial between the cables and *EE*. The tension value of one of these springs can be set to a desired value if the system has available degrees of redundancy to do so. One degree of redundancy must be left free to fulfill the restriction of tension boundaries in each cable as stated in (Clément Gosselin & Grenier, 2011). With this assumption, this analysis can be done for any cable-driven fully constraint robot with $r > 2$ or a suspended kind of $r > 1$ (Clément Gosselin & Grenier, 2011)(J. Merlet, 2016).

Several studies about the stiffness of elastic mechanisms can be found like the numerical and experimental estimation of the stiffness model with lumped parameters (Carbone, 2011). When an elasto-geometrical analysis is performed in a cable system, some specific sources of error can be analyzed due to geometric and mechanical uncertainties as demonstrated in (Baklouti et al., 2018). In addition, the elastic behavior imposed on the robot with the use of springs provides a compliant mechanism in the *EE* that creates a more secure environment for the interaction between humans and CDPRs. As explained in (Van Ham et al., 2009), “a compliant actuator will allow deviations from its own equilibrium position, depending on the applied external force”. This elastic mechanism could be upgraded to act as tensegrity manipulators like in (Lessard et al., 2016)(Sumi et al., 2017). Due to the elastic consideration, the compliant actuator can be considered as a tensegrity based compliant mechanism defined as (Moon et al., 2013).

3.3.- Hypothesis and objectives

The main objective proposed in this chapter is to validate the feasibility of the proposed compliant mechanism to control an articulated platform of 7 DoF: 6 DoF of their main link and 1 DoF of the joining of two links. Also, the performance and the validity of the kinetostatic analysis is needed to perform. The results of this experiments could serve as a basis for the exertion of wrenches in a distributed region of a body or different limbs of an articulated body.

The main hypothesis establishes that an accurate position control for the second body of a reconfigurable end-effector of 1 inner DoF can be developed. Knowing the values of force that this control are imposing to the entire end-effector to add the usual control algorithms related with rigid end-effectors.

The experiment needed to validate this hypothesis is focused on the secondary end-effector, the corresponding cable attached to it and the compliant mechanism. So this, the analysis was made by fixing the main body of the platform to the ground to focus on one compliant actuator and the forces applied to the first body.

Experiments conducted in this chapter considered a generic eight cable prototype with an end effector of six degrees of freedom, so $r = 2$ degrees of redundancy were available where one of them was used to ensure that all cables were tensioned, and the other was set to control the cable tension and its related elongation to move the secondary end-effector.

Main chapter's objectives:

- Validate the feasibility of the compliant mechanism to use it in the quality improvement of the underwater simulator.

Chapter's hypotheses:

- The second body of the end-effector can be controlled in position with an accuracy of a relative error lower than 10% by using the developed and specified compliant mechanism.

3.4.- Redundancy resolution for the passive reconfigurable platform

Cable robots are usually redundantly actuated to increase their workspace to make them robust under faults or for increasing their dexterity (M Gouttefarde et al., 2015). The degree of redundancy of a robot is defined as:

$$r = m - n \quad (3.1)$$

where n is the degree of freedom of the mechanism; m is the number of actuators; and r is the degree of redundancy. When $r > 0$, for a given wrench applied at the EE , there exists infinite solutions for the values of tension in the m cables. Those solutions are the different tension configurations of the CDPR. This tension distribution can be defined in the following way (M Gouttefarde et al., 2015):

$$\boldsymbol{\tau} = -(\mathbf{A})^\dagger \mathbf{W} + \mathbf{N}\boldsymbol{\lambda} \quad (3.2)$$

where $\boldsymbol{\tau}$ is the m -dimension vector of the tension of the cables; $(\mathbf{A})^\dagger$ is the Moore–Penrose pseudoinverse of the non-square wrench matrix of the mechanism; $\mathbf{W}$ is the vector of external wrench applied in the EE ; $\mathbf{N}$ is the $(m \times r)$ matrix that defines the null space basis of $\mathbf{A}$; and $\boldsymbol{\lambda} = [\lambda_1, \dots, \lambda_r]$ is an arbitrary vector in the null space basis. This vector allows the selection of any tension distribution in cables ($\boldsymbol{\tau}$) that fulfils the constraints of maximum (Marc Gouttefarde et al., 2007) and minimum (P. Liu et al., 2014) tension in each cable.

The left side of Equation (3.2) is the particular solution of the tension distribution that has a minimum 2-norm. The right side is the homogeneous solution that spans all possible tension configurations. Applying the principle of virtual work and screw theory, wrench matrix ($\mathbf{A}$) is defined as the transpose of the Jacobian matrix of the mechanism (Taghirad, 2013):

$$\mathbf{A} = \begin{bmatrix} \mathbf{u}_1 & \dots & \mathbf{u}_n \\ \mathbf{p}_1 \times \mathbf{u}_1 & \dots & \mathbf{p}_n \times \mathbf{u}_n \end{bmatrix} \quad (3.3)$$

where $\mathbf{u}_i$ is the unitary vector with the same direction of the force that the i -cable exerts to EE and $\mathbf{p}_i$ is the vector of the point of the EE where that force is applied. Using the concept of Screw Theory (Davidson et al., 2004) for simplicity of calculus, the origin of vector $\mathbf{p}_i$ is considered the EE center of mass (Davidson et al., 2004).

The tension value was imposed in the redundancy analysis from chapter 2 to obtain a feasible tension configuration. The value of this tension is the force that the compliant actuator exerts on the end effector when the second body of the reconfigurable platform is being controlled.

The elongation of the springs is proportional to the tension force measured in the springs attached to the end-effector (EE) (τ_j^*) ($j = n + 1, \dots, m - 1$):

$$\tau_j^* = k_j(l_j - l_{0j}) = k_j \delta l_j \quad (3.4)$$

where k_j is the stiffness of spring j and l_{0j} is its length when unloaded. τ_j^* is the tension measured in the springs from the compliant mechanisms while τ_j is related to the tension of the rest of the cables that go from the pulleys to the EE . The value of δl_j ($j = n + 1, \dots, m - 1$) is set as the necessary conditions to obtain the tension configuration of the m cables. As described in chapter 2, the appropriate number of compliant mechanisms to keep the position completely restrained is $m - (n + 1) = r - 1$.

The tension distribution can be obtained using Equation (3.2), however, the values of τ_j^* of the $r - 1$ springs are imposed attending to the desired position of the second body of the platform. These values are read from their corresponding sensors attached to their springs. With this consideration, the $r - 1$ unknowns lost by the imposition of tension values for the compliant mechanism, the $m + r$ initial unknowns are reduced to $m + 1$.

As mentioned before, we let the variable λ_r unconstrained in order to fulfill the restriction of making every cable pulling. There were m equations and $m + 1$ unknown values. This expression, derived from Equation (3.2) has the form:

$$\begin{bmatrix} \tau_1 \\ \vdots \\ \tau_n \\ \tau_{n+1}^* \\ \vdots \\ \tau_{m-1}^* \\ \tau_m \end{bmatrix} = - (A)^\dagger W + N \begin{bmatrix} \lambda_1 \\ \vdots \\ \lambda_r \end{bmatrix} \quad (3.5)$$

In Equation (3.2), there were m independent variables from the tension provided by cables plus r independent variables from the degrees of redundancy with m equations. In Equation (3.5), as the $r - 1$ values of τ_j^* are set to a desired value, there are only $m - (r - 1)$ unknowns from the cable tension and r for handling the nullspace. Letting one degree of redundancy in order to have some freedom of choice in the cable tension configuration avoids configurations where a cable tries to push. So that the end effector can be substituted by a mechanism with $(r - 1)$ DoF. The range of possible values of l_j increases with the range of τ_j^*/k_j , as seen in Equation (3.4).

The m actuators of the CDPR, situated in the fixed base, can fully control the $(m - 1)$ degrees of freedom of the entire EE , considered as a reconfigurable platform. Although some links of the reconfigurable EE are under high cable tension for maintaining the imposed equilibrium of Equation (3.2), there are some links whose tension comes only from the values of the desired l_j . That tension depends on the stiffness of the close-loop mechanism of the EE .

3.5.- Mechanism Description

The mechanism is a cable-driven parallel robot with a reconfigurable end effector of 1 inner DoF. As seen in Figure 3.3, all cables parted from fixed points where m actuated winches released or collected the cables. Those winches were situated at generic fixed points. In this way, the motors that act on the winches could control the length of all the cables. The analysis of this article focused on the modeling of a special cable configuration, denominated compliant actuator, that was able to control both bodies of the end effector. The compliant actuator parted from B_i to A_i and D and was controlled by the motorized winch situated in B_i , however in C_i , this cable was divided into two cables that provided mechanical tension to EE_1 and EE_2 at the same time.

Figure 3.5. Schematic description of a cable-driven robot with reconfigurable platform of two bodies (EE_1 and EE_2). The compliant actuator that parted from B_i to A_i and D could control both bodies of the reconfigurable end effector at the same time.

A priori, the compliant actuator had one controlled input and two outputs in each body of the platform, which is why a linear sensor was situated between C_i and A_i . This linear sensor provided the elongation of that part of the compliant actuator, which was related to its mechanical tension. In order to amplify the elongation/tension value, a spring was added in series in that cable. The linear sensor passed through the inside of the spring to provide the elongation of the section $\overline{C_i A_i}$ and so, its tension value. This value was obtained by using Equation (3.4). The length between B_i and C_i is l_B , l_D is the length from C_i to D , and l_A is the length measured by the linear sensor from C_i to A_i . The value of l_B is controlled by a winch, l_D is a section of cable with a defined length (when no forces are applied) and l_A is the value measured with the linear sensor.

The mechanism designed to be the EE of the robot had one DoF. The two links or bodies of this mechanism were designated as EE_1 and EE_2 . The body EE_2 had a cylindrical articulation (D) that could move freely through a linear guide. Despite this articulation has 2 DoF, just its linear movement is analyzed and controlled. This linear rod was solidary to EE_1 with direction z' and passed through E. $\{M\}:O' - x', y', z'$ is the frame linked in the center of the top face of EE_1 .

The cable $B_i C_i$ had a spring attached at its end with stiffness k_i . This spring defined the line $A_i C_i$, whose length was measured by using the linear position encoder. These types of encoders add a tension in C_i with direction to $C_i A_i$ that was characterized in order to be considered in the model. It also needed to measure the values of the spring stiffness considering them in the function of elongation $C_i A_i$. This model $k_i(\|C_i A_i\|)$ can be obtained from a traction test of the spring.

The segment of cables that did not have a spring are modeled as a linear spring in order to consider variations of length due to cable deformation; in addition, the cable was considered without mass:

Assumption 1: *Cables have negligible mass.*

Tension force in cable $B_i C_i$ is exerted due to the weight of the body EE_2 . To maintain this tension, D_i has to be at a lower height than C_i in the fixed frame $\{F\}:O - x^F, y^F, z^F$:

$$(\overrightarrow{C_i A_i} + \overrightarrow{A_i O'})^F \cdot \hat{k}^F < (\overrightarrow{D_i E_i} + \overrightarrow{E_i O'})^F \cdot \hat{k}^F \quad (3.6)$$

Using Graph Theory and Screw Theory (P. Lambert & Herder, 2016), it is possible to represent, after simplification, this mechanism like that seen in Figure 3.6.

Figure 3.6. Graphical simplified representation of robot topology. Red line is the l_B cable with impose tension exerted by the actuator; the green line is l_D that transmits effort to the second end effector and the blue line l_A represents the linear sensor link.

As seen in Fig. 3.6, all parallel legs $Base - B_i - EE_1$ can be reduced to a unique wrench obtained from the linear combination of all the wrenches of the legs. The $(r - 1)$ legs that have an additional end effector are analyzed in the following section.

3.6.- Kinetostatic resolution

The objective of this analysis is to find the relation between the length of l_B and the distance between the two bodies of the end effector along its degree of freedom restricted by the rod. The compliant actuator length (l_B) was controlled by a motorized winch fixed in B_i . Therefore, this problem focuses on the behavior of the compliant actuator. Previously, it was defined how it is possible to exert tension in the compliant actuator handling the perturbation that this cable exerts in the resultant wrench applied in EE_1 . Considering that all cables can compensate the effect of the compliant actuator as seen in Equation (3.5), it is possible to impose forces and torques values on EE_1 with independence on the value of tension provided by the compliant actuator. However, in order to set the desired wrench in EE_1 , it is necessary to know the tension value of the compliant actuator. The linear sensor according to Equation (3.4) provides that measure indirectly. For this analysis, the EE_1 was considered fixed in space in order to focus this study on the compliant actuator. This assumption was made by imposing null resultant wrenches in EE_1 .

In order to reach the proposed objectives, a direct kinetostatic problem was formulated in this section. The objective of the analysis was to calculate the length $\|\overrightarrow{ED}\|$, designated with l_E , that is the distance between the two bodies of the end effector. The known values are the position of the points in the fixed base B_i , and the position and orientation of EE_1 . That attitude of EE_1 can be specified with Euler angles or quaternions. The homogeneous transformation matrix from $\{M\}$ to $\{F\}$ is:

$$T_M^F = \begin{bmatrix} R_M^F & \overrightarrow{OO'} \\ 0 & 1 \end{bmatrix} \quad (3.7)$$

Where R_M^F is the rotation matrix between the two reference frames. The location of the attachment points of the cable to EE_1 : $(\overrightarrow{A_iO'})^M$ is also known, which can be seen from the fixed frame by using:

$$(\overrightarrow{A_iO'})^F = R_M^F (\overrightarrow{A_iO'})^M \quad (3.8)$$

In the kinetostatic analysis, dynamic efforts are neglected by performing low accelerated movements. Only the weight of EE is considered as an external wrench $\mathbf{W}$ to be substituted in Equation (3.2). The value of l_E is one of the independent variables and its value will be one of the $(m - 1)$ reference values for commanding the robot (n values for exerting a desired wrench to EE_1 and defining its position and one value for setting l_E). The length $\|\overrightarrow{A_iC_i}\|$ is known by using a linear encoder so the tension in A_iC_i can be obtained using Equation (3.4).

The objective of the process was to obtain the direct kinetostatic resolution. The value of l_E was obtained for each value of l_B , which is the length from $\mathbf{B}$ to $\mathbf{C}$. Due to the longitudinal deformation of the cable when tension is exerted and the uncertainty of how the tension of $\mathbf{BC}$ cable is exerted in the $\mathbf{AC}$ cable and $\mathbf{CD}$ cable, it is necessary to add a linear sensor to obtain additional information of the length and tension in cable $\mathbf{AC}$.

Cable tension is related to geometric configuration. This is because tension in the cables is exerted only along their axis so they reconfigure themselves to align their geometric axis with the force vectors. This issue demands an iterative resolution that combines the geometric resolution with the wrench in order to converge to the precise solution for each sample of the position of the robot. In Figure 3.7, the scheme for the resolution of the kinetostatic of the compliant actuator of the robot can be seen. A priori, known values are l_B^l , defined by the actuator and the winch that releases the cable. The value of l_A is also known and is directly provided by the linear sensor. Geometric resolution assumes that cables are inextensible and the desired l_E^l value is obtained, as seen in Section 3.5. However, because we considered deformable cables, we needed to know the tension in each cable to obtain their elongation. This relation is the same as Equation (3.4) because the cable has been modeled as a linear spring. Once the updated values of cable length have been obtained, another iteration can be performed to reach more accurate results.

In this analysis, the velocities and accelerations of the robot were small enough to neglect the dynamic effects and the position and tension changes were very small. Therefore, only one geometric and wrench iteration

are solved in each sample. If the system moves faster or if a more precise solution is needed, the number of iterations and their convergence could be resized for each value of l_B .

Figure 3.7. Scheme of the resolution of the kinetostatic of the compliant actuator of the robot.

3.7.- Geometric Resolution

The first step of the analysis was to define the geometric place where point C_i could be situated. Considering the lengths l_B and $\|\vec{C_iA_i}\|$, C_i was situated at the intersection of the two spheres with those radiuses and centered in B_i and A_i , respectively. This region is a circumference centered in:

$$(\vec{C_i})^F = \vec{B_i}^F + \frac{(\vec{B_iA_i})^F}{\|\vec{B_iA_i}\|} \|\vec{B_iC_i}^*\| \quad (3.9)$$

The distance between the point where the cable begins (B_i), and the center of the circumference is obtained by considering the intersection of the circumferences centered in B_i and A_i with radius l_B and $\|\vec{A_iC_i}\|$:

$$\|\vec{B_iC_i}^*\| = \frac{(\|\vec{B_iA_i}\|^2 - \|\vec{A_iC_i}\|^2 + l_B^2)}{2\|\vec{B_iA_i}\|} \quad (3.10)$$

The cable has two deviation angles from the theoretical straight line between B_i and A_i due to cable tension τ_C : angle β , in the pulley or winch B_i and α in the anchor point of EE . These angles are measured in the plane that contains the triangle $B_iC_iA_i$ and are obtained with:

$$\beta = \cos^{-1} \left(\frac{\|\vec{B_iC_i}^*\|}{l_B} \right) \quad (3.11)$$

$$\alpha = \cos^{-1} \left(\frac{\|\vec{B_iA_i}\| - \|\vec{B_iC_i}^*\|}{\|\vec{A_iC_i}\|} \right) \quad (3.12)$$

Knowing this, the radius of the circumference is:

$$h = l_B \sin \beta = l_B \sin \left(\cos^{-1} \left(\frac{\|\vec{B_iC_i}^*\|}{l_B} \right) \right) \quad (3.13)$$

$$h = l_B \sqrt{1 - \left(\frac{\|\vec{B_iC_i}^*\|}{l_B} \right)^2} \quad (3.14)$$

The radius is strictly bigger than zero ($h > 0$). This circumference has high relevance in this analysis so reference frame $\{\mathcal{C}\}:\mathcal{C}^* - x^{\mathcal{C}}, y^{\mathcal{C}}, z^{\mathcal{C}}$ was defined in order to clarify the analysis. $x^{\mathcal{C}}$ has the direction of the line between B_i and A_i ; $y^{\mathcal{C}}$ is perpendicular to this line and perpendicular to z^F . The direction and orientation of this frame is defined in Figure 3.5.

Point $\mathcal{C}$ is situated at a point of that circumference. That position depends on the wrench exerted by EE_2 in the system and in the length of $\|\overrightarrow{CD}\|$. The position of $\mathcal{C}^{\mathcal{C}} = [C_x^{\mathcal{C}}, C_y^{\mathcal{C}}, C_z^{\mathcal{C}}]^T$ with respect to $\{\mathcal{C}\}$ is:

$$C_x^{\mathcal{C}} = 0 \quad (3.15)$$

$$C_y^{\mathcal{C}} = h \cos \theta \quad (3.16)$$

$$C_z^{\mathcal{C}} = h \sin \theta \quad (3.17)$$

Point $\mathcal{C}$ expressed in $\{\mathcal{F}\}$ is:

$$\mathcal{C}_i^F = T_{\mathcal{C}}^F \mathcal{C}^{\mathcal{C}} + \mathcal{C}^{*F} \quad (3.18)$$

With $T_{\mathcal{C}}^F$ the transformation matrix from $\{\mathcal{C}\}$ to $\{\mathcal{F}\}$:

$$T_{\mathcal{C}}^F = \begin{bmatrix} R_{\mathcal{C}}^F & \overrightarrow{OC_i^*} \\ 0 & 1 \end{bmatrix} \quad (3.19)$$

In Equations (16) and (17), the value of θ is not known. Additional information related to EE_2 is needed to solve the equations. The position of D has to be along the line ED and it is a function of l_E :

$$\mathcal{D}^F = \mathcal{D}^F(l_E) = \mathcal{O}^{*F} + T_M^F \left(\left(\overrightarrow{O'E} \right)^M - l_E \frac{\overrightarrow{ED}}{\|\overrightarrow{ED}\|} \right)^M \quad (3.20)$$

Matrix T_M^F is defined in Equation (7) and the vertical rod has the direction of $\vec{z}^M$. The unknown value of θ defines infinite planes $\Pi = \Pi(\theta)$ defined by the points $\mathcal{B}_i^F, \mathcal{A}_i^F, \mathcal{C}_i^F$ and also $\mathcal{C}_i^{*F}$. Formulating it in the Hessian normal form, its normal vector ($\hat{n}$) is:

$$\hat{n}^{\mathcal{C}} = -\frac{1}{h} \frac{\partial \mathcal{C}^{\mathcal{C}}}{\partial \theta} = [0, \sin \theta, -\cos \theta]^T \quad (3.21)$$

$$\hat{n}^F = T_{\mathcal{C}}^F \hat{n}^{\mathcal{C}} \quad (3.22)$$

Assumption 2: The mass of C_i can be neglected.

With the consideration of the assumption 2, it is possible to analyze the equilibrium of forces applied in C_i as coplanar vectors, as is shown in Figure 3.8.

Figure 3.8. Equilibrium of forces in point C_i .

The relation between θ and l_E is obtained from the intersection between Π and $l_E \hat{k}^M$:

$$\mathbf{D}^F \cdot \hat{\mathbf{n}}^F = 0 \quad (3.23)$$

To obtain the isolated value of l_E , Eq. (3.20) can be rewritten as:

$$\mathbf{D}^F = \mathbf{E}^F - l_E \mathbf{V}^F \quad (3.24)$$

Combining Equations (23) and (24) and applying distributive property, we can obtain:

$$\mathbf{E}^F \hat{\mathbf{n}}^F - l_E \mathbf{V}^F \hat{\mathbf{n}}^F = 0 \quad (3.25)$$

$$l_E = \frac{\mathbf{E}^F \hat{\mathbf{n}}^F}{\mathbf{V}^F \hat{\mathbf{n}}^F} \quad (3.26)$$

The operation of Equation (25) needs the vector $\hat{\mathbf{n}}^F$ that defines Π , which depends on the unknown angle θ . In order to obtain this, it is necessary to impose the known value of l_D to the distance between C_i and D .

$$\mathbf{D}^F - \mathbf{C}_i^F = \mathbf{E}^F - \frac{\mathbf{E}^F \hat{\mathbf{n}}^F}{\mathbf{V}^F \hat{\mathbf{n}}^F} \mathbf{V}^F - \mathbf{C}_i^F \quad (3.27)$$

$$\|\mathbf{D}^F - \mathbf{C}_i^F\| = l_D \quad (3.28)$$

Regarding the position of the linear rod $\overrightarrow{\mathbf{E}_i \mathbf{D}_i}$, solutions of the direct kinetostatic problem are shown in Fig. 3.9. It is known that C_i is situated in a semi-circumference (black line in Fig. 3.7) and point D is in plane Π , which contains points C_i^F, C_i^{*F}, D^F so the geometrical shape of the possible positions of D is a torus of $R = \|\overrightarrow{C_i C_i^*}\|$ and $r = \|\overrightarrow{C_i D}\|$. If the conditions of positive traction in all of the cables are imposed, it can be seen that point C_i has to be lower than the horizontal plane that contains C_i^{*F} to maintain the tensions τ_A and τ_B , as was already proposed in Eq. (3.4). In addition, the interior face of the torus corresponded to configurations where C_i has to exert an effort against the three cables, which is impossible with this mechanical design (unless punctual high dynamics effects are considered).

Figure 3.9. Geometric region of valid existence of point D.

With the previous boundaries considered, as represented in Fig. 3.9, apparently there exists one or two solutions for the direct kinetostatic problem depending on the position and orientation of the vertical rod. However, a third condition is based on the projection of the weight of EE_2 , $-m_2\vec{g}^F$ on $\overrightarrow{ED}^F$. This projected tension has to provide a positive value of τ_D . A mathematic way to see this condition is:

$$(\overrightarrow{ED})^F \cdot (\overrightarrow{C_iD})^F > 0 \quad (3.29)$$

EE_1 is not able to turn more than $\pi/2$ rad in x^F or in y^F , so the vector of weight projection on the vertical rod is always from E to D , and Equation (3.27) is always valid. Considering these three additional restrictions based on the imposition of positive traction, we passed from the consideration of until four solutions to have a unique one.

3.8.- Wrench Resolution

Once the direct kinematic problem is solved by obtaining the value of l_D in function of l_B , it is possible to obtain the wrenches in the three cables that make up the compliant actuator. Values of tension in each cable are needed to calculate the linear elongation of cables, check if the system is between the tension limits, and calculate torque required by the actuator.

A priori, the only known value is τ_A , which is provided by the relation defined in Equation (3.4) by the linear sensor. Figure 3.9 represents the triangle of equilibrium of tensions, which can be deduced from the equilibrium of forces shown in Figure 6 by imposing the wrench closure in point C_i . As it was assumed that point C is massless, all tensions are coplanar in the plane Π . This equilibrium is expressed (considering unitary vectors) as:

$$\tau_B(\widehat{C_iB})^F + \tau_C(\widehat{C_iD})^F + \tau_A(\widehat{C_iA})^F = 0 \quad (3.30)$$

Angles α and β are calculated once the value of θ is obtained. The direction and sense of τ_B is known because it is coincident with the l_B direction, so it only needs one more value, which can be the value of τ_B , the value of τ_C , or the direction of τ_C in plane Π . This last value was used in this analysis.

Figure 3.10.- Equilibrium of forces at point C_i .

In order to obtain the direction of τ_C in plane Π , φ is obtained from geometric relations as:

$$\varphi = \cos^{-1} \left(\frac{\overrightarrow{DC} \cdot (-\overrightarrow{BA})}{\|\overrightarrow{DC}\| \|\overrightarrow{BA}\|} \right) \quad (3.31)$$

Knowing the direction of the tension τ_C , all cable tension can be obtained by imposing the equilibrium of wrenches, as seen in Figure 8. The stiffness of each cable is:

$$k_i = \frac{EA}{L_i} \quad (3.32)$$

where E is Young's Modulus; A is the section of the cable; and L_i is the length of the cable. With the stiffness and cable tension, the longitudinal deformation can be obtained by using Eq. (3.4).

Figure 3.11. Wrenches applied to end effector 2.

In order to use Equation (2), the value of the external wrenches needs to be defined, which are responsible for the tension of the cables. Considering the separated wrench of EE_1 and EE_2 , $\mathbf{W}$ is defined as:

$$\mathbf{W}^F = \begin{bmatrix} \mathbf{F} \\ \mathbf{M}_o \end{bmatrix} = \mathbf{W}_{EE_1}^F + \mathbf{W}_{EE_2}^F \quad (3.33)$$

Wrenches applied on both end effectors are considered from the geometric center of EE_1 . The symmetry and constant density along its volume is considered in order to set the following external wrench:

$$\mathbf{W}_{EE_1}^F = \begin{bmatrix} -(m_1)\mathbf{g}^F \\ 0 \end{bmatrix} \quad (3.34)$$

3.8.1. Secondary End-effector influence

As this is a kinetostatic analysis, EE_2 is static, so:

$$G_L = \tau_{CL} \quad (3.35)$$

Wrenches applied on EE_2 have to be applied in a perpendicular direction of the rod:

$$\mathbf{W}_{EE_2}^F = \begin{bmatrix} \mathbf{G}_T^F - \boldsymbol{\tau}_{C_T}^F \\ \mathbf{R}_M^F(\overrightarrow{O'D})^M \times (\mathbf{G}_T^F - \boldsymbol{\tau}_{C_T}^F) \end{bmatrix} \quad (3.36)$$

The value of the wrench exerted in EE_1 is due to the mass of EE_1 . Wrench exerted on EE_2 is due to the components of the mass of EE_2 perpendicular to the rod as no friction is considered between the cylindrical joint of D and the rod. The projection of EE_2 weight over the rod is:

$$\mathbf{G}_L^F = \mathbf{T}_M^F(\mathbf{G}^F \cdot \mathbf{k}^M) \quad (3.37)$$

The perpendicular projection of this weight is:

$$\mathbf{G}_T^F = \mathbf{G}^F - \mathbf{G}_L^F = m\mathbf{g}^F - \mathbf{G}_L^F \quad (3.38)$$

The last step is to find the components of τ_C over the rod. The direction of τ_C is given by $\overrightarrow{C_iD}$ and the rod direction is given by $\overrightarrow{ED}$. The angle between $\overrightarrow{C_iD}$ and $\overrightarrow{ED}$ is:

$$\cos(\widehat{\overrightarrow{C_iD}, \overrightarrow{ED}}) = \frac{(\overrightarrow{C_iD} \cdot \overrightarrow{ED})}{\|\overrightarrow{C_iD}\| \|\overrightarrow{ED}\|} \quad (3.39)$$

$$\tau_C = \frac{\tau_{CL}}{\cos(\widehat{\overrightarrow{C_iD}, \overrightarrow{ED}})} \quad (3.40)$$

Where at statics $\tau_{CL} = G_L$ due to the neglecting friction and dynamic effects, as seen in Fig. 3.11.

3.9.- Results

3.9.1.- Simulated results

A model of a robot with the compliant actuator was developed in the multi-body dynamic simulator MSC ADAMS. This software can obtain values that are difficult to measure like tension in different section of the cables, forces and reactions in all joints and bodies, friction and elongation in pulleys and cables, etc. In addition, multiple kind of motions can be imposed in the actuators.

In this model, linear and vertical motion were imposed on the end of the white cable shown in Figure 3.12. This cable passed along a pulley whose parameters are listed in Table 3.1. The cable was attached to point C, which was modeled with a negligible mass of 10^{-2} kg. Properties of the nylon cable modeled are shown in Table 3.2.

The EE_1 has been modeled as a rigid body fixed in space. Redundancy should be able to provide this position even when the perturbation of the compliant actuator is exerted. The join between A_i and C is the spring that adds the needed flexibility to make the linear sensor measurement more sensible to small tension variations in that branch of the cable. In D is the EE_2 , which was modeled as a body with cylindrical restriction with the vertical rod fixed to EE_1 . The cable between D and C was modeled with a spring of 222 mm to analyze its elastic behavior. Spring stiffness was obtained by using Equation (3.32) and the values from Table 3.2. Spring stiffness for this cable was 4.83 N/m.

Point C is a solid sphere of 10^{-2} kg. In B_i , it is situated in a pulley with a radius of 2.5×10^{-3} m that was able to rotate around the axis of its hole and on its vertical axis. In this model, the force was applied by exerting a position control on the final part of the cable (red ball in Figure 3.12). The proposed algorithm allowed

us to find the position of D for each length of the cable. The cable was modeled with the parameters shown in Table 3.2.

The actuated cable was modeled with the values in Table 3.2. Elastic behavior and friction with the pulley were modeled, however, mass and inertia were neglected due to the reduced section of the cable. The modeling of the cable was a linear spring.

Figure 3.12. Model of the compliant actuator in the multi-body dynamic simulator MSC ADAMS.

Table 3.1 Pulley parameters

Parameters	Values
Diameter (mm)	5
Width (mm)	4
Depth (mm)	0.5

Table 3.2 Cable parameters

Parameters	Values
Diameter (mm)	0.6
Young ¹ (Pa)	3.9×10^9
Density (kg/m ³)	1150

¹ Young's Modulus.

Table 3.3 shows the initial positions of each relevant part of the model. Point references and the reference frame can be seen in Figure 3.5. All values were measured from the frame fixed frame O.

Table 3.3 Position of relevant parts

Parameters	X (mm)	Y (mm)	Z (mm)
O'	355	477	607
A_i	310	377	575
D	355	417	502
C	193	358	642
B_i	23	953	902

EE_1 was fixed as well as the vertical with the rod that is attached to it, to make possible the isolated analysis of the compliant actuator. EE_2 , with 0.3 kg of mass, could move along the rod without friction with the unique actuation of cable CD, represented as a spring in Figure 3.12. In order to leave the end effector moving without attachment, we needed to know the forces that acted on it which were provided by using the method proposed in this article. The simulated experiment, which is shown in graphs as the last 10 s, and each one of the 400 samples was taken each 0.025 s. The speed of the control cable (l_B) was approximately 18 mm/s (0.018 m/s). As can be seen in the following graphs, this speed was slow enough to neglect the dynamic effects.

Finally, the sensorized cable AC was modeled as a spring. This spring stiffness was obtained by using a traction test of the spring, as can be seen in Figure 3.13. The linear region of the spring was considered from 0 to 120 mm and its stiffness, considered constant, as $k_A = 63.6 \frac{N}{m}$. This maximum length for the spring imposes a

restriction in the movement of EE_2 . In that maximum elongation, the force achievable was 7.5 N (+2.2 N of the force of the linear encoder) = 9.7 N.

Figure 3.13. A) Curve of the spring situated as link between A and C: Tension vs. elongation; B) Device where traction test was done: Mecnesh Imperial 1000.

The linear sensor used was a *LX EP-40* of *UniMeasure* modeled as a constant force of 2.2 N compressing the spring. This force was measured and is also specified in the sensor datasheet. So, the stiffness of the link which connects A with C was modeled as a spring with an additional compressing force of 2.2 N. The maximum force achievable with springs was 7.5 N + 2.2 N = 9.7 N. At the beginning of the simulated experiment, the system was pre-tensed to begin in an equilibrium state where the tension in all cables had a non-zero value. This previous pre-tension mode was not shown because it was considered as not relevant data in this analysis.

A comparison between the simulation and calculated values of the method proposed in this article are shown below. In Figure 10, the position of EE_2 along the rod, in red, represents the simulated values and the values obtained with kinetostatic method are in black. The available length of the rod was 260 mm and the analysis was made from -100 to -270.

The input values in the theoretical method were obtained by using data acquired in a simulation with MSC ADAMS. Figure 3.14 shows the value obtained of LD, figure 3.15 shows the value obtained of LB and LA, which is the measure of the linear sensor. Looking at the configuration of the system (Fig. 3.5), it can be seen that it was difficult to reach positions close to EE_1 with EE_2 , which was due to the high tension needed to reach that, and can likely be deduced by extrapolating the data from Figures 3.16 and 3.17.

With this method, the tension values of the tree cables could be obtained. Figure 3.16 shows the tension values of cable B, which is related with the torque that the motor has to exert, additionally, this tension value is highly related to the deformation of this cable as the length is proportional to the cable deformation as seen in Eq. (3.32).

Figure 3.14. Comparison of the theoretical position of D (black) and the simulated position of D (red)

Figure 3.15. A) Values of LA simulated that are considered in the kinetostatic method as the sensor value. B) Input values of LB, length of controlled cable

Figure 3.16. Comparison of the theoretical tension of B cable (blue) and the simulated tension of B cable (green)

Figure 3.17. Comparison of the theoretical tension of D cable (blue) and the simulated tension of D cable (green)

In order to perform the first validation of these results, the error was measured between the simulated results and the results from this method. Table 3.4 shows the mean and standard deviation of the absolute error of each sample:

$$\varepsilon_a = Value_{calculated} - Value_{simulated} \quad (3.41)$$

Table 3.4. Absolute error between the model and simulation

Parameters	Values	Parameters	Values
Mean error LD	-1.53 mm	Std. Dev. ¹ LD	1.71 mm
Mean error τ_B	-0.05 N	Std. Dev. ¹ τ_B	0.27 N
Mean error τ_D	0.01 N	Std. Dev. ¹ τ_D	0.01 N

¹ Standard Deviation.

Table 3.5 considers the absolute imprecision values, which considered the absolute value in order to obtain the mean. The standard deviation with absolute value was also considered:

$$Ea = \frac{|Value_{calculated} - Value_{simulated}|}{n^o \text{ of samples}} \quad (3.42)$$

Table 3.5. Absolute imprecision between model and simulation

Parameters	Values	Parameters	Values
Mean error LD	2.09 mm	Std. Dev. ¹ LD	0.95 mm
Mean error τ_B	0.24 N	Std. Dev. ¹ τ_B	0.13 N
Mean error τ_D	0.01 N	Std. Dev. ¹ τ_D	0.01 N

¹ Standard Deviation.

Table 3.6 shows the mean of the relative error between the calculated and simulated results with its value along all samples. This error is defined as:

$$\varepsilon_R = \frac{\varepsilon_A}{Value_{simulated}} \quad (3.43)$$

Table 3.6. Relative error between model and simulation

Parameters	Values
Mean error LD	0.63%
Mean error τ_B	-1.74%
Mean error τ_D	0.34%

3.9.2. - Experimental results

In order to verify that the simulated model was valid, a prototype was built to compare the real world with the simulated results. The dimensions of the dynamic model in MSC ADAMS and the prototype are defined in Table 3.7 (values are considered in the reference frames shown).

Table 3.7. Dimensions of the robot

Parameters	Values
O^F (mm)	[355, 447, 622]
A^M (mm)	[-45, -70, -30-17] ¹
B^F (mm)	[23, 953, 902]
E^M (mm)	[0, -30, -30]
m_{EE1} (Kg)	0.4
m_{EE2} (Kg)	0.2
l_D (mm) ²	222

¹ Position of linear encoder is 17 mm under the vertex of the body; ² Length of cable between C and D when not under tension.

As seen in Figure 3.18C, EE_2 was formed by a mechanism with two inner degrees of freedom (rotations) that allowed the alignment of cable l_D with the central axis of the rod. This was made to reduce the friction effects and to ensure that the l_D cable projection always ended at the same point of the axis of the rod. The distance of l_D was considered from C_i until the red point, and not only the physical cable length. The linear encoder from Figure

3.16B exerted 2.2 N of force to EE_2 due to the tension of its cable. This force was added to the EE_2 mass in the model.

A scheme of the experimental set up is shown in Figure 17. The incremental linear encoder used was an LX-EP-40 of UniMeasure. It is able to measure the linear distance of the cable deployed from its base. The cable of this encoder was under a nominal tension of 2.2 N. The measure resolution was $2.45 \pm 0.35\%$ counts/mm, giving a precision of 0.4 mm/count. The sensing element of the encoder is an optical incremental encoder with electrical outputs consisting of two square wave, TTL level output channels in quadrature. One of these encoders was used to find the value of l_A , as seen in Figure 16b, which is the encoder that will be situated in the robot in normal duty. The second linear encoder was used to measure the distance of the EE_2 from E, denominated as l_D , and checked if the real position corresponded with the theoretical.

Figure 3.18. A) General view of the CDRP where it shows point B_i where the compliant actuator begins and the controlled length l_B ; B) EE_1 with a fixed position, with the compliant actuator coming from the left l_B and split in l_D attached to the EE_2 and l_A . It can be seen that l_A is made of a spring attached to C_i and A_i and a thin blue cable inside the spring coming from the linear encoder output (marked with a red dot); C) EE_2 with the central axis of the rod marked with a red dot and the extrapolation of the cable marked with a white discontinuous line.

The length of the cable was measured by using the encoder of the motor. This motor coiled the cable around a pulley of 14 mm in diameter that was attached to the shaft of the motor. The motor was a RE 13 Graphite Brushes motor of 3 Watts of Maxon that provided a nominal torque of 2.42×10^{-3} Nm. The motor had a reducer of 275:1, so the nominal torque in the shaft of the motor was 0.67 Nm. As the pulley where the cable was coiled had a diameter of 14 mm, the nominal tension exerted to it had a value of 95 N. The motor obtained its power from the amplifier ADS 50/5 4-Q-DC of Maxon, which applied a current control of the motor.

The encoders of the actuators were attached to the shaft of the motor, before the reduction. These encoders were of the MR Type S, 16 CPT, 2 Channels of Maxon. They detect 16 counts per turn of the motor, or $16 \times 275 = 4400$ counts per turn of the shaft of the entire actuator. Each count appears after 0.08° , which corresponds in the linear displacement of the cable to one count each of 9.7×10^{-6} m.

The precision provided by the encoders was enough to work with an accuracy in the experiment of 0.5 mm.

All of the signals were handled by using a CompactRIO 9081 from National Instruments that had a CPU Dual-Core 1.06 GHz, 2 GB DRAM, 16 GB storage, and a FPGA Virtex-6 LX75. The modules used were the analog input module AI-NI9205 and the analog output module AI NI-9264.

The absolute accuracy of the analog input module was 3.23×10^{-3} V with a random noise of 2.4×10^{-4} Vrms and a sensitivity of 9.6×10^{-5} V. The calibration of this module was done by using the self-calibration software. However, the signals acquired by this module were TTL signals from the encoders, so it did not need more accuracy than this kind of signal requires.

The analog output module requires more precision as this voltage is responsible for controlling the current of the actuator. This module had a resolution of 16 bits, the gain error for this experiment was 8×10^{-3} V and the offset error was 10^{-2} V. Those values were enough to set the current value of the motor.

Figure 3.19. Scheme of the signals considered. Two linear encoders read the values of l_A and l_D while the value of l_B is obtained by using the encoder of the motor. In blue are the lines of the incoming values from the sensors, in red are the power lines, and in green are the outgoing signals to control the motors. The processor was a CompactRIO 9081 with modules for analog input and output.

In Fig. 3.18–20, the values obtained for l_B , l_A , and l_D with the MSC ADAMS simulation are compared with the values obtained from the real prototype. In order to make an appropriate comparison, the samples of the real values of l_B were situated over the corresponding samples of the simulated values, that were from sample 56 to sample 156. The same correspondence of the samples considered the values of l_A and l_D had the same scale for the comparison. The values of l_B were obtained by a PID control loop in the actuator where the value of l_B acts as feedback.

Due to limitations in the prototype, only a limited range of movement was achieved. In order to reach higher positions with EE_2 , longer springs are needed as the required values of l_A are high when EE_2 is situated at a higher position than -200 mm, as seen in Figure 3.22. As seen before, the range of linear stiffness of the spring was from 0 to 120 mm so the values corresponding the values are inside that range as shown in Figure 3.21. In order to focus this analysis in terms of the behavior of the compliant actuator, EE_1 was attached to the fixed frame.

Additional tests were conducted to calculate the repeatability and statistical distributions. Two experiments were undertaken by displacing the EE_2 from its lower position to the upper position and another two experiments were developed by displacing the EE_2 from its upper position to the lower position. This method should be valid for the two types of displacements so the two measures were considered together as experiments with the same working conditions to obtain the statistical distributions.

Figure 3.20. Comparison of simulated value of and real world results for l_B

Figure 3.21. Comparison of the simulated and real world results for l_A . Dotted line corresponds to the simulated results with MSC ADAMS. Red line corresponds to the value of l_A in an experiment where EE_2 goes up from its lower position. Blue line corresponds to the value of l_A in an experiment where EE_2 goes down from its upper position.

Figure 3.22. Comparison of the simulated and real world results for l_D . Red line corresponds to the value of l_D in an experiment where EE_2 goes up from its lower position. Blue line corresponds to the value of l_D in an experiment where EE_2 goes down from its upper position.

The repeatability of the measures was based on the method presented in (Taghirad, 2013). The values of the range of the measures can be seen in Figures 3.23A and 3.23B.

Figure 3.23. Average range of the measured values for calculating the repeatability. (a) From the two measures of l_A ; (b) From the two measures of l_D .

Two different measures from different experiments were performed. The maximum value of the range of the measure of l_A was 6.3 mm while the mean value of its range was 2.2 mm. The maximum value of the range of the value of l_D was 4.2 mm while the mean value of its range was 1.7 mm. The standard deviation due to repeatability is calculated and the results are shown in Table 3.8.

Table 3.8. Range of the measuring

Parameters	l_A (mm)	l_D (mm)
Max. range	6.2	4.2
Mean range	2.2	1.7
Max. Std. Dev	5.5	3.7
Mean Std. Dev	1.9	1.5

Figure 3.24. The blue graph is the error between the simulated value and the real value. Red dotted line is the mean value of the error between the real measure and the simulated one. (a) Values of the measure of l_A ; (b) Values of the measure of l_D .

Measuring the difference between the real values and the simulated ones allows for the visualization of the deviation of the measurements from the desired values. The maximum error between the real and simulated measures is shown in Figure 3.24 and Table 3.9 as well as the mean error along the whole range of the mechanism.

Table 3.9. *Deviation from simulated and real measures*

Parameters	l_A (mm)	l_B (mm)
Max. error	-3.5	-3.9
Min. error	0	-0.6
Mean error	-1.2	-1.9

Considering that the range of l_A was [54, 94] mm and the range of l_B was [-237, -202] mm. The relative error comparing the mean error with the range of each measure is shown in Table 3.10.

Table 3.10. *Relative error between simulation and real prototype*

Parameters	Values
Mean error LA	3.0%
Mean error LD	5.3%

3.10.- Discussion

The method presented in this chapter gives the position of the second body of the end effector and tension of all parts of the compliant actuator with limited accuracy for any given value of l_B . Appropriate results have been obtained with this mechanism for the intended application due to the intended human–robot collaboration and the high elastic effects present in the robot. The experimental tests validated the simulated model with a 5.4% error between the real experiment and the simulation and 0.63% between the theoretical value and the simulation, which correspond to a mean error of 1.7 ± 1.5 mm between the real and simulation and 1.5 ± 1.7 mm between simulation and theoretical. Those results can be seen as suitable for the intended application and validate the main hypothesis as well as the feasibility of the simulation. However, improved designs and algorithms need to be developed in order to exert the wrenches for the underwater simulation to different parts of a reconfigurable body, as seen in following chapters.

The following values are needed as input:

Position and shape of the first end effector.

Position of the points where cables are deployed from the fixed structure.

Characteristics of the cable, spring, and linear sensor.

Mass of the two end effectors.

Constant length of the cable attached to the second end effector.

Variable length of control cable (l_B) and measure of the linear encoder as the input of the algorithm.

The analysis proposed was kinetostatic so dynamic effects due to high velocities and accelerated masses were neglected. This consideration is valid when slow movements are made. In this case, l_B moved with a speed of 18 mm/s (0.018 m/s), which, as seen, was low enough to neglect the dynamic effects because the non-linear effects in acceleration or deceleration stages are not observed.

The number of samples considered was 400 samples in the simulated experiment and 8000 in the real world experiment. In each sample, the mathematic method ran performing iterations of the algorithm shown in Figure 3.7.

The results obtained with the analysis shown in this study allows the creation of the control position of a cable driven parallel robot with two end effectors configured in the way defined with a cable that exerts its effort over the two bodies. Considering this methodology of measuring with a linear encoder in the intermediate links, it could be possible to increase the number of end effectors and complexity of the system.

In addition, by using the information provided by the sensor and the spring attached to it, it is possible to calculate tension in all cables. Knowing the tension in control cable (l_B), it is easier to develop better joint control of the actuator by adding this variable tension to the control scheme. Tension in cable l_D can be useful in those cases where there is interaction with humans or delicate environments to restrict the cable tension to increase security. The value of tension of cable l_A allows for the control of EE_1 due to its direct influence being one of the wrenches applied by the n cables.

The position of the point C, could be seen as the resolution of the geometrico-static problem of an under constrained CDPR with two cables (l_A and l_B) and a pose-dependent external wrench (Carricato & Merlet, 2010) that could also be solved by applying optimization methods like branch-and-bound as in (Collard & Cardou,

2013). However, those methods are not yet fast enough for real-time and the experiments described in this chapter have been developed at low speeds and accelerations. In (Berti et al., 2013), interval analysis was proposed to solve the forward kinetostatic problem for a 3-3 CDPR while in (Carricato et al., 2012) the inverse kinetostatic problem was solved for a CDPR with 4 cables.

The dynamic model used in MSC ADAMS simulated a totally controlled environment to test the validity of this algorithm. It can be seen that the error between both results is acceptable for slow applications that do not need high precision or high speed, like underwater robots or rehabilitation devices.

The dynamic model of MSC ADAMS was validated with real world experiments developed with a prototype with the same configuration as the dynamic model. There were some sources of errors between the prototype and model like the friction effects not modeled, deviation of the cable of the linear encoder before getting into the spring, or the presence of electric noise in some measurements.

Several assumptions were imposed in order to make this analysis possible:

Mass of C was neglected.

Mass of cables was neglected.

Pulleys' geometry and their dynamics were neglected.

The mass of point C was very small because in the actual prototype, it is made by a system of bolts and nuts of low weight. In the simulated model, this weight was considered to be 10^{-2} kg. This hypothesis was crucial in this analysis to work with just one plane Π .

Nylon cables have a density of $1150 \text{ (kg/m}^3\text{)}$ and an area of 0.28 mm^2 . For a length of 700 mm, the cable weight is 0.22 grams, which in this analysis could be easily neglected. With this assumption, the catenary effects were not considered

It is noticeable that the mean error between the real and simulated measures had a negative value for the position of the second body of the end effector as well as a negative value for the elongation of the spring with the sensor. This effect could have appeared due to a non-precise characterization of the elastic effects of the nylon cable that in the real case could have a lower stiffness than in the theoretical and simulations. The young modulus of the cable has been defined in table 3.8 because it is the parameter related to nylon. However, the behavior of the nylon varies with the use and other conditions as seen in (Taghirad, 2013). In addition, the neglecting of the mass of the cables and the mass of C could have relevance in the appearance of that error. In (Baklouti et al., 2018), different sources of errors are explained when an elasto-geometrical model is used with cable mechanism. Similarities between the graphs presented in both articles are easily detected.

One way to reduce this error could be the consideration of a cable stiffness of lower values than the theoretic value of the nylon and the consideration of the cable mass.

Finally, the dynamics and geometry of the pulleys were considered in the dynamic simulator, however, the algorithm considered them as points in their center.

4.MULTI-BODY RESOLUTION BASED ON ELASTIC ENERGY DISTRIBUTION

4.1.- Introduction

One of the main differences between a CDPR and a usual parallel robot (Jean-Pierre Merlet, 2006) is the flexibility and elasticity of the cables (Ottaviano & Castelli, 2010). This characteristic was used to control reconfigurable end-effectors with compliant actuators, in chapter 3 (Rodriguez-Barroso et al., 2018), where the actuation of a single cable exerts its influence on two different bodies. As observed, the input from one actuator can provide a displacement and a force at the same time. The relationship between those two magnitudes can be obtained from the elastic behavior that can be expressed with the Hooke's Law. As the actuated cable that conform one of the compliant mechanisms is a SISO system to control the displacement or force of the second end-effector, a proposed energetic approach to this problem could merge those two variables into one. This energetic-based approach to the control of the articulated platform proposed several advantages:

1. Capability to impose energetic values to the secondaries end-effectors instead of displacements or forces, useful when the body under the simulation has unknown stiffness values or unpredicted motion like in the case of humans, or machines, or materials with non-linear stiffness like polymers.
2. Real-time knowledge of the energy stored in the elastic components by using a direct expression to relate the elastic potential energy with the tension distribution.
3. Fast calculation of the regions of feasible elastic energy for each cable and for the whole robot.
4. Energetic minimization after imposing the restrictions related with the desired displacements or forces in the secondary end-effector.

The scope of this chapter is to use energy analysis to simplify the resolution of the movement of the second end-effector to have a better understanding and improved control and design for the application of the underwater wrenches to the end-effector. One illustrative experiment to test the correspondence of the energy with the displacement and the force is the application of this method to a gripper design like the shown in Fig. 4.1. One finger of the gripper, that corresponds to the second end-effector can be moved when it is not holding any object and can apply force when it is grasping an object or pressing with the other gripper finger corresponding to the main end-effector. This design evolves from the generic mechanism developed in chapter 3 to simplify the feasible movements of the compliant mechanism and simplify the resolution of the geometrico-static equations. In addition, the analysis of a gripper allows to check the behavior in a freely movement state and also in a state where the gripper is holding an object, that is related with displacements and wrench acting simultaneously.

The mechanism shown in fig. 4.1 has a main end-effector (the cubic shape) that can move inside its workspace by pulling from all the cables attached to it from the inertial frame. Its position is defined by the geometric relations, assuming that the cable model is a linear spring defined by the actual spring that is between the cable and the end-effector (blue cable in Figure 4.1). The end-effector speed is obtained from the inverse kinematics. The actuators, situated outside the workspace, coil each cable by defining their deployed length and applying the desired tension. Parallel robots' kinematics developments can be seen in (Jean-Pierre Merlet, 2006), while the basic specific relationship with cable-driven robots can be found in (Ebert-Uphoff & Voglewede, 2004).

The energy-based method allows this magnitude to be used to consider either the tension or the linear elongation of the cable or even other physical effects related with the energy magnitude such as electromagnetics forces. Some methods based on energy have recently been used to solve the forward kinematics, as seen in (Liwen et al., 2015)(Pott & Tempel, 2018). The imposed values of tension in redundant cables could be used to set softer variations in the torque of the motor or for modifying the stiffness of the links if they have nonlinear springs. If the linear deformation is imposed, it can be used for controlling reconfigurable end-effectors, like in (Barbazzà, Oscari, et al., 2017)(Barbazzà, Zanutto, et al., 2017)(Rodriguez-Barroso et al., 2018).

4.3.- Hypothesis and objectives

The main objective is to consider the elastic energy stored in the cables and in the entire robot to directly impose the desired energy of any cable for controlling its position and force. These magnitudes will be related with the stiffness of the mechanism to control one of the compliant mechanisms as a SISO system while knowing the stiffness value. Also, the range of energy that each cable can handle will be obtained for a given main end-effector position and set of applied forces. This energy analysis will provide the range of movement of those cables that correspond to compliant mechanisms that exert their actuation on more than one body of the end-effector.

The second objective is to apply the close-form energetic expressions to control a gripper attached to the main body defined as the secondary end-effector. This gripper while opening requires a displacement control while in a close state requires a force control. Knowing the stiffness of the mechanism, an energetic approach should be enough to handle both variables. In addition, by knowing the expression for energy, an analysis of its topology can be done. With this knowledge, it is possible to obtain the direction of the energy boundaries imposed in cables and reduce the computation time while working with known shapes related with the energy distribution.

The main hypothesis that lead to the proposed experiment is that with an accurate model of the stiffness of the system it is possible to control the two end-effectors of a reconfigurable platform by setting potential elastic energy to obtain the position and force applied to the second end-effector respect the first one.

The proposed working scheme is shown in Fig.2: The elastic energy stored in the main body of the end-effector “Rigid EE” and each cable is obtained from the position (J) and the wrench applied (F). This total elastic energy provides the allowed elastic energy of each cable that will be used to control the position and force of the second body, acting in this case as a gripper. Finally, the influence of this second body in the first body will require to modify the forces acting in the first body and to recalculate its elastic energetic possibilities and the position and force with the updated state.

Figure 4.2. Scheme of the proposed methodology for obtaining the aperture and force exerted by the gripper of the reconfigurable end-effector by considering the boundaries imposed by the rigid end-effector model.

Main chapter's objectives:

1. Design a CDPR with reconfigurable end-effector suitable to be controlled without any measurement sensor or actuator in the end-effector.
2. Find an equation to relate the potential energy stored by the components of the CDPR with the tension distribution.
3. Use the proposed mechanism to control a gripper in its both states: closed and opened.

Chapter's hypothesis:

1. Knowing the stiffness values of the compliant mechanism it is possible to control the position or the force of the secondary end-effector regarding on the movability of the end-effector imposed by external circumstances.

4.4.- Elastic Energy Expressions

The expression for the tension distribution in a redundant CDPR is defined in (M Gouttefarde et al., 2015) as

$$\boldsymbol{\tau} = (\mathbf{J}^T)^\dagger \mathbf{F}_{ext} + \mathbf{N}(\mathbf{J})\boldsymbol{\lambda} \quad (4.1)$$

where $(\mathbf{J}^T)^\dagger$ is the $(m \times n)$ matrix corresponding to the pseudoinverse Moore–Penrose of the transpose of the Jacobian matrix. $\mathbf{F}_{ext}$ is n-vector of the external wrench applied to the end-effector. $\mathbf{N}(\mathbf{J})$ is the $(m \times r)$ matrix of the nullspace of the Jacobian matrix, and $\boldsymbol{\lambda}$ is an r -vector of values over the basis defined by the nullspace.

4.4.1 Potential Energy of Cables

The potential energy of one i -cable is defined considering the model of a cable as a linear spring with stiffness k_i . The energy stored in each spring is defined as

$$U_i = \frac{k_i \delta_i^2}{2} \quad (4.2)$$

where δ_i is the linear deformation of the i -cable. This linear deformation is proportional to the mechanical tension of the i -cable, as seen in the following equation:

$$\tau_i = k_i \delta_i \quad (4.3)$$

It is possible to obtain the potential energy stored in the i -cable related to its mechanical tension by combining Equations (4.2) and (4.3):

$$U_i = \frac{\tau_i^2}{2k_i} \quad (4.4)$$

In Equation (4.1), the nullspace is considered in order to modify the tension distribution along all cables by maintaining the constant value of the resultant wrench in the end effector. This freedom provided by the redundant configuration of the robot can be reflected in the value of the potential energy stored in each one of the cables. In order to clarify the equations, Eq. (4.1) is rewritten in a simpler notation:

$$\boldsymbol{\tau} = \mathbf{B} + \mathbf{A}\boldsymbol{\lambda} \quad (4.5)$$

Where

$$\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1r} \\ a_{21} & a_{22} & \cdots & a_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mr} \end{pmatrix} \quad (4.6)$$

$$\mathbf{B} = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{pmatrix} \quad (4.7)$$

By combining Equations (4.4) and (4.5), the expression of the potential energy for the i -cable in function of the nullspace variables is obtained:

$$U_i = \frac{(b_i + \sum_{j=1}^r a_{ij}\lambda_j)^2}{2k_i} \quad (4.8)$$

By solving the squared term and simplifying the previous equation, the following expression is obtained:

$$U_i = \frac{\lambda^T \mathbf{P}_i \lambda + \mathbf{Q}_i^T \lambda + R_i}{2k_i} \quad (4.9)$$

With

$$\mathbf{P}_i = \begin{pmatrix} a_{i1}^2 & a_{i1}a_{i2} & \cdots & a_{i1}a_{ir} \\ a_{i1}a_{i2} & a_{i2}^2 & \cdots & a_{i2}a_{ir} \\ \vdots & \vdots & \ddots & \vdots \\ a_{ir}a_{i1} & a_{ir}a_{i2} & \cdots & a_{ir}^2 \end{pmatrix} \quad (4.10)$$

$$\mathbf{Q}_i = 2 \begin{pmatrix} b_i a_{i1} \\ b_i a_{i2} \\ \vdots \\ b_i a_{ir} \end{pmatrix} \quad (4.11)$$

$$R_i = b_i^2 \quad (4.12)$$

With Equation (4.9), it is possible to vary the energy stored in each cable without exerting any influence on the total wrench of the end effector. In order to describe the potential energy stored in all the cables, the m equations corresponding to the potential energy of each cable seen in (8) need to be merged into:

$$U = \sum_{i=1}^m U_i \quad (4.13)$$

By substituting Equation (9) into Equation (13), the expression for the total energy stored in all cables in the function of the nullspace variables is:

$$U = \frac{1}{2} \left(\lambda^T \left(\sum_{i=1}^m \frac{\mathbf{P}_i}{k_i} \right) \lambda + \left(\sum_{i=1}^m \frac{\mathbf{Q}_i}{k_i} \right) \lambda + \sum_{i=1}^m \frac{R_i}{k_i} \right) \quad (4.14)$$

The potential energy stored in the cables is a function of the dimension and position of the robot, the wrench applied to the end effector, the cable stiffness, and the tension distribution along the cables:

$$U = U(\mathbf{J}, \mathbf{F}_{ext}, \lambda, \mathbf{k}) \quad (4.15)$$

4.5.- Energetic Restrictions

Each cable is limited to a certain range of tensions higher than zero. This range of tensions is denoted as:

$$0 < \tau_{min} < \tau < \tau_{max} \quad (4.16)$$

The minimum and maximum tension are chosen for working in the linear part of the elastic equation of the spring. Tensions lower than τ_{min} do not produce elongation, while tensions higher than τ_{max} make the spring get into the plasticity zone. Those tension value limits can be converted into energy by using the stiffness of each cable, as seen in Equation (4.4):

$$U_{imin} = \frac{\tau_{imin}^2}{2k_i} \quad (4.17)$$

$$U_{imax} = \frac{\tau_{imax}^2}{2k_i} \quad (4.18)$$

It is possible to obtain the tension distribution that makes the cable achieve its maximum or minimum tension. By substituting Eq. (4.17) and (4.18) into Eq. (4.9), the expressions of $\Lambda_{i_{max}}, \Lambda_{i_{min}} \subset \mathbb{R}^r$ are obtained, which represent the feasible nullspace boundaries:

$$U_{i_{min}} = U_{i \rightarrow \Lambda_{i_{min}, \dots, r}}(\lambda) = 0 \quad (4.19)$$

$$U_{i_{max}} = U_{i \rightarrow \Lambda_{i_{max}, \dots, r}}(\lambda) = 0 \quad (4.20)$$

The result of this substitution is $2r$ hypersurfaces: r for $\Lambda_{i_{max}}$, and r for $\Lambda_{i_{min}}$. These hypersurfaces correspond to those regions of the nullspace that generate a tension distribution that exerts its maximum and minimum potential energy in the i -cable, respectively. In order to consider only those values that the i -cable can handle by pulling, it is necessary to take one value of each hypersurface and check if all the tension values are positive by using Eq. (4.1) or (4.5). Each one of the $2r$ border hypersurfaces, $\Lambda_{i_{min}}, \Lambda_{i_{max}} \subset \mathbb{R}^r$, corresponding to each i -cable, set the boundaries for the feasible potential energy hypersurface, Ω_i , which is defined in the $\mathbb{R}^{r+1}$ space. The added dimension represents the value of the i -cable potential energy over the r nullspace variables. In order to have a clearer view of this energy shape, the energy is projected over any two nullspace variables ($\lambda_\alpha, \lambda_\beta$). That $\mathbb{R}^3$ surface corresponds to a parabolic cylinder, as demonstrated in the append A. This means that it is possible to represent the feasible potential energy of each cable by projecting it into each pair of nullspace variables. The hyper-surfaces $\Lambda_{i_{min}}$ and $\Lambda_{i_{max}}$ divide the $\mathbb{R}^{r+1}$ space into two different regions: the feasible region and the regions where the tension cable is outside the desired range.

If the potential energy of the i -cable is considered to depend only on the value of two nullspace variables ($\lambda_\alpha, \lambda_\beta$), the parabolic cylinder has quadratic terms that can be linearized by rotating the quadric and aligning it with the axis of the variables ($\lambda_\alpha, \lambda_\beta$). This is made by calculating the eigenvectors of the matrix of quadratic terms $\mathbf{P}_i$. The diagonalized matrix is:

$$\mathbf{P}_i^* = \begin{pmatrix} a_{i\alpha}^2 + a_{i\beta}^2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (4.21)$$

with only one non-null eigenvalue. The corresponding eigenvectors, expressed as the changing base matrix, are:

$$\mathbf{V}^* = \begin{pmatrix} -\frac{a_{i\alpha}}{a_{i\beta}} & \frac{a_{i\beta}}{a_{i\alpha}} & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (4.22)$$

It is seen that in Equation (4.23), there is only one non-null eigenvalue whose eigenvector is $\mathbf{V}_1^* = \left[-\frac{a_{i\alpha}}{a_{i\beta}}, 1, 0 \right]$. This eigenvector defines the direction of the lines that contain the improper centers of the quadric. This direction coincides with those lines that contain the points with the same value of potential energy. In this way, the projected direction of the lines over λ_α and λ_β of the maximum and minimum potential energy are defined by the eigenvector corresponding to the non-null eigenvalue $\mathbf{V}_1^*$. Indeed, any allowed value of potential energy in any cable produces a line of valid points in the nullspace with the direction $\mathbf{V}_1^*$ when the energy is defined over any two variables ($\lambda_\alpha, \lambda_\beta$).

Finally, the total energy stored in all the cables defines a hypersurface, Ω , that corresponds to an elliptic paraboloid, as seen in Appendix B, when it is projected into any pair of nullspace variables. The feasible region for the total potential energy is defined by the intersection of the m hypersurfaces that correspond to each i -cable:

$$\Omega = \bigcap_{i=1}^m \Omega_i \quad (4.23)$$

4.5.1.- Selection of elastic energy for a single cable

It is possible to set any desired value to the r nullspace variables λ in order to set the corresponding desired potential energy values in each cable. For each variable λ whose value is established, the volume of the total potential energy feasible region, Ω , is reduced because, by setting the value of a nullspace variable, the dimension corresponding to that variable collapses into a defined point.

The selection of the energy of each cable can be used for multiple purposes, for example, setting a desired tension in a cable or setting a desired linear deformation in its springs. Each imposed cable energy value restricts one of the available nullspace variables, so only r imposed values of tension or deformation can be set as the desired value.

The region of the nullspace of the i -cable that provides its desired potential energy is obtained by using Equation (4.9) in a similar way as Eq. (4.19) and (4.20):

$$U_{desired} = U_i \rightarrow \Lambda_{i_{desired}, \dots, (r-1)}^*(\lambda) = \mathbf{0} \quad (4.24)$$

Considering the shape of the quadric already analyzed for $\mathbb{R}^3$ for the potential energy of a cable, the line of all nullspace values that provides a certain potential energy in a cable can be obtained directly. Once the desired value of potential energy is set, one point of this line is provided by Equation (4.24), while the direction of the line is provided by Equation (4.22).

Once the restrictions have been applied, the polytope that establishes the cable tension distribution loses one dimension, shrinking the feasible workspace in the nullspace, and the remaining degrees of freedom can be considered for setting new values of potential energy in other cables.

4.6. Passive reconfigurable end-effector analysis

The method presented in previous sections allows force or deformation to be imposed in any cable and to determine the available range of elastic energy that any other cable can store without altering the end-effector wrench.

In this section, the mechanism proposed in Figure 4.1 is analyzed to control the movement of the gripper. This mechanism is based on the CDPR with compliant actuators shown in chapter 3 and (Rodriguez-Barroso et al., 2018) and allows two different bodies of the same end-effector to move by taking advantage of the redundancy and elasticity of the cables. The application of the proposed method determines the range of movement of one or several grippers to identify whether it is possible to close it and to determine the size of object that the gripper can handle for certain positions and the wrench applied to the end-effector. This gripper has its movement restricted to 1 DoF. A vertical linear guide attached to the main body of the end-effector imposes this restriction.

In Figure 4.1, the energy applied by the motor to cable j is exerted on cables j_A and j_B . While j_A imposes its tension to the end-effector, j_B moves the gripper. The initial displacement L_2 is measured when the tension in j_A is τ_{min} , and the relation between cables deformation and gripper movement is defined by:

$$\delta_j = \delta_{j_A} = \delta_{j_B} \quad (4.25)$$

while the relation between each cable tension is:

$$\tau_j = \tau_{j_A} + \tau_{j_B} = \tau_{j_A} + \|F_{j_{BW}}^\parallel\| + F_{j_{BA}} \quad (4.26)$$

where $\|F_{j_{BW}}^\parallel\|$ is the weight of the gripper projected over the hanging cable. Cable j_B turns around a ring or a pulley whose constant friction term can be added to $F_{i_{BW}}$ with $F_{j_{BA}}$, that is, the term related to the pulley friction and cable weight.

$$F_{j_{BW}} = -F_{j_{BW}}(\hat{k} \cdot \hat{k}_M) \hat{k}_M = F_{j_{BW}} \Omega \quad (4.27)$$

$$F_{j_{BW}}^\perp = -F_{j_{BW}} \hat{k} - F_{j_{BW}} \quad (4.28)$$

Figure 4.3. Weight force acting on the gripper. It is projected in parallel to the cable, imposing the tension τ_{jB} , and perpendicular to the cable, acting on the main body of the end effector.

The compliant actuator exerts the tension from j_A on the main body of the end-effector as well as the force due to the gripper weight, as represented in fig. 3. The force exerted by this compliant actuator to the main body at point $\mathbf{p}_j$ (blue dot of Figure 1) is:

$$\mathbf{F}_{jE_1} = \tau_{jA} \hat{\mathbf{u}}_i + \tau_{jB} \hat{\mathbf{u}}_i + \mathbf{F}_{jBW}^{\parallel} + \mathbf{F}_{jBA} \quad (4.29)$$

In addition, the force exerted at point $(\mathbf{p}_j + \mathbf{L}_1)$ by the weight of the gripper is:

$$\mathbf{F}_{jE_2} = \mathbf{F}_{jBW}^{\perp} \quad (4.30)$$

It is assumed that j_A and j_B are parallel. Mechanically, this assumption can be built by using a ring with a small radius or even by passing the cable j_B inside the coils of the spring K_A . Due to the low displacement and low weight of the gripper with respect to the main body, $\|\mathbf{L}_1\|$ is assumed to be constant for all values of L_2 :

$$(L_2 + \max(\delta_{jB})) - (L_2 - \min(\delta_{jB})) \ll \|\mathbf{L}_1\| \quad (4.31)$$

The structure matrix ($\mathbf{J}^T$) used in Equation (1) can be written considering this compliant actuator as:

$$\mathbf{F}_E = \mathbf{J}^T \begin{pmatrix} \tau_i \\ \vdots \\ \tau_m \end{pmatrix} + \mathbf{J}_{weight}^T \begin{pmatrix} F_{jBW} \\ \vdots \\ F_{rBW} \end{pmatrix} \quad (4.32)$$

The gripper weight is included so the m actuated cables define the well-known structure matrix ($\mathbf{J}^T$), while the influence of the gripper weight in the main body of the end-effector is defined by ($\mathbf{J}_{weight}^T$). For a mechanism with redundant actuation, the maximum number of grippers is r . The structure matrix is:

$$\mathbf{J}^T = \begin{pmatrix} \hat{\mathbf{u}}_i & \dots & \hat{\mathbf{u}}_m \\ \mathbf{p}_i \times \hat{\mathbf{u}}_i & \dots & \mathbf{p}_m \times \hat{\mathbf{u}}_m \end{pmatrix} \quad (4.33)$$

where Equation (4.26) has been used to set Equation (4.32) as a function of τ_j and F_{jBW} . The wrench applied by the gripper weight to the end effector is related to:

$$\mathbf{J}_{weight}^T = \begin{pmatrix} \mathbf{\Omega} + (-\hat{\mathbf{k}} - \mathbf{\Omega}) \\ \mathbf{p}_j \times \mathbf{\Omega} + (\mathbf{p}_j + \mathbf{L}_{1j}) \times (-\hat{\mathbf{k}} - \mathbf{\Omega}) \end{pmatrix} \quad (4.34)$$

By simplifying Equation (34), we obtain:

$$\mathbf{J}_{weight}^T = \begin{pmatrix} -\hat{\mathbf{k}} \\ \mathbf{p}_j \times (-\hat{\mathbf{k}}) + \mathbf{L}_{1j} \times (-\hat{\mathbf{k}} - \mathbf{\Omega}) \end{pmatrix} \quad (4.35)$$

The term J_{weight}^T from Equation (4.35) adds as many columns as compliant actuators j are added to the end-effector.

4.7.- Position Reference

The position reference will be used when the gripper is open without handling any object. A direct relationship between the energy that the actuator has to exert and the gripper position can be obtained by considering the total energy of cable 1:

$$U_1 = U_{1A} + U_{1B} = U_{1A} + U_{min} + (\|F_{1BW}\| + F_{jBA})\delta_1 \quad (4.36)$$

With U_{1A} chosen from the available values defined by (4.23) and U_{min} , the initial energy stored in the mechanism is determined considering the potential energy reference when the spring from j_A has its minimum energy. By combining (4.36) and (4.2), it is possible to obtain the position of the gripper with respect to the energy that the actuator of cable 1, U_1 , has to exert:

$$\delta_1 = \delta_1(U_1) = \frac{-(\|F_{1BW}\| + F_{jBA}) + \sqrt{(\|F_{1BW}\| + F_{jBA})^2 + 2K_A(U_1 + U_{min})}}{K_A} \quad (4.37)$$

In this way, it is possible to know the energy needed by the actuator of cable 1 to set the desired position of gripper 1. However, previous restrictions already set in cable 1_A have to be preserved. Those energy boundaries are defined as:

$$U_{1min} = U_{1Amin} + \|F_{1BW}\| + F_{jBA}\delta_1 \quad (4.38)$$

$$U_{1max} = U_{1Amax} + \|F_{1BW}\| + F_{jBA}\delta_1 \quad (4.39)$$

4.8.- Force Reference

When the gripper is closed or it is grabbing an object, the increasing energy of the gripper does not impose a movement but a force when the handled object is considered rigid. Due to the spring K_{1B} , the energy of this grabbing force can be directly added to the energy from the gripper weight by adding this term to (4.36). This expression acts when the grippers are closed ($\delta_1 > L_{21}$):

$$U_1 = (U_{1A} + U_{min}) + \frac{K_B(\delta_1 - L_{21})^2}{2} + (\|F_{1BW}\| + F_{jBA})L_{21} \quad (4.40)$$

Where L_{21} is the free range of displacement of the gripper before closing. The value of this length can be obtained by different methods like looking for the energy peaks and trend variations, vision or contact sensors. The structure matrices from Equation (4.32) do not vary because the tension increase in cable 1_B is compensated by the reaction force from the gripper to the main body. In this way, once the contact of the gripper with a rigid object is detected, the second part of Equation (40) acts and the force is controlled in the gripper instead of its position. The expression for the cable elongation is obtained in the same way as Equation (4.37)

$$\delta_1 = \frac{(K_B L_{21} + \sqrt{(K_B L_{21})^2 - 2\Delta(K_A + K_B)})}{K_A + K_B} \quad (4.41)$$

With

$$\Delta = (\|F_{1BW}\| + F_{jBA})L_{21} + \frac{K_B L_{21}^2}{2} - U_1 + U_{min} \quad (4.42)$$

The force exerted by the gripper is defined as:

$$\begin{aligned} F_{1BA} &= K_B(\delta_1 - L_{21}), & \text{if } \delta_1 > L_{21} \\ F_{1BA} &= 0, & \text{if } \delta_1 \leq L_{21} \end{aligned} \quad (4.43)$$

With the energy boundaries in function of force defined as:

$$U_{1min} = U_{Amin} + \frac{K_A L_{12}^2}{2} + (\|F\|_{BW} + F_{jBA})L_{21} \quad (4.44)$$

$$U_{1max} = U_{Amax} + (\|F\|_{BW} + F_{jBA})L_{21} + \frac{F_{1BA}^2}{2K_B} \quad (4.45)$$

4.9.- Theoretical Results

4.9.1. Energy Distribution of the Rigid End-Effector

The experiment consists of setting specific forces in the end-effector of a CDPR with eight cables, while two additional requirements are set for two different cables.

The inertial frame of the robot is a parallelepiped of 10×5 m and a height of 6 m, and cables are deployed from the four upper corners of this frame. The end effector is a 150 kg cube with 1 m sides situated at the coordinates $\chi = (7, 4, 1.5 \mid 0, 0, \frac{\pi}{6})[\text{m} \mid \text{rad}]$, seen from the fixed frame $\{\mathcal{F}\}$ and under the influence of the external force $F_{ext} = (200, 0, -1470 \mid -500, 0, 0)[\text{N} \mid \text{Nm}]$ applied in the center of the cube.

The connection of the cables from the inertial frame to the end effector have the following correspondence, according to Figure 4 and Table 1.

The results obtained for a robot with eight cables and six degrees of freedom are easy to show because they can be expressed in 3D space.

Depending on the nullspace position, the potential energy of each cable corresponds to a parabolic cylinder, as seen in Fig. 4.5. The value of λ is the same for all cables, and the tension boundaries are not set yet.

Figure 4.4. Cable-driven parallel robot scheme and the points for cable connections between the inertial frame and the end effector.

Table 4.1. Connection points for cables $r = 2$

Inertial Frame	End-Effector	Cable Name
P1	U4, D2	Cable1, Cable2
P2	U1, D3	Cable3, Cable4
P3	U2, D4	Cable5, Cable6
P4	U3, D1	Cable7, Cable8

Figure 4.5. Surface corresponding to the potential energy of each cable as a function of the nullspace variables

Figure 4.6. Red region (Ω_i): feasible region in the nullspace that provides a cable tension inside the allowable value. Black line (A_{imin}): region where one or more cables achieve the minimum allowable tension value. Red line (A_{imax}): region where one or more cables achieve the maximum allowable tension value.

The allowed tension values chosen for each cable are between 50 and 500 N. The spring stiffness is 10^3 N/m. The boundary values for the energy are obtained with Equations (4.17) and (4.18), and they are 1.25 and 320 J. The regions of feasible energy for each cable (Ω_i) are obtained by using Equations (4.19) and (4.20). Those regions and their boundaries $\Lambda_{i_{min}}$ and $\Lambda_{i_{max}}$ are shown in Figure 4.6.

The intersection of all the nullspace regions that define feasible tension values in each cable (Ω_i) provides the nullspace region (Ω), where all cables fulfil their tension conditions. The potential energy in all the cables was also obtained in (4.14). The representation of the total potential energy with the region of total feasible tension is shown in Figure 7. It is observed that its shape corresponds to an elliptic paraboloid.

It is also interesting to analyze those regions of maximum potential energy, ($\Lambda_{i_{max}}$), achieved with a negative tension in any link. A cable-driven robot cannot achieve this configuration, but it can be obtained by using a parallel robot with rigid links, which is able to exert compression efforts on the end effector. Fig. 4.8 represents the feasible nullspace region for a cable-driven robot and the region for a parallel robot with rigid links under the same working conditions. The region corresponding to the cable is a subset of the region corresponding to the robot with rigid links. Only those regions where the boundary of the cable robot coincides with the boundary of to the rigid robot correspond to points where a link exerts maximum effort. So, in Figure 4.8, it is impossible to achieve the maximum tension in any cable before having another cable lose its tension under the lower limit.

Figure 4.7. Surface section that represents the potential energy of all cables. The red polygon defines the region of the nullspace that provides feasible tension values in all cables.

Figure 4.8. Red region (Ω): region of the nullspace that provides a feasible tension in all cables. Black region (Ω^*): region of the nullspace that provides feasible efforts in all the rigid links of a parallel robot with the same configuration of the cable robot.

In order to set the desired tension and deformation values in each cable, Equations (4.2) and (4.4) can be used. For this example, the desired linear deformation in cable 8 is 0.447 m, so following Eq. (4.2), the energy of cable 8 is set to 100 J.

By imposing the energetic restriction in cable 8, its nullspace region of feasible tension collapses from a 2D surface to a 2D line. Figure 4.9 shows this line of feasible tension for achieving every restriction and the total elastic potential energy stored in the cables that depends on the nullspace variables.

Figure 4.9. The blue 3D curve represents the potential energy stored in all cables that can be achieved by maintaining the condition of setting a deformation in the cable 8 of 0.2 m. The projection of this curve over the horizontal plane provides feasible nullspace variables. Coordinates are $[\lambda_1, \lambda_2, U]$

With the remaining degree of freedom, it is possible to set the energy in another cable. For example, the range of potential energy available for cable 1 is obtained by substituting the values of the available nullspace variables in (9), which gives a range of $U_1 \in (1.25, 18.36)$ J, as seen in Figure 10. This range of energy can be used to impose values of deformation in cable 1 according to (4.2): $\delta_1 \in (50, 191.6)10^{-3}$ m. Alternatively, it can be used to impose a tension value according to (4.4): $\tau_1 \in (50, 191.6)$ N. If no restriction needs to be added to cable 1, the nullspace position for this cable could be that which minimizes the total potential energy. As seen in Figure 4.9, this position is $\lambda_1 \in (-12.39, 101.5)$, which provides a total potential energy of $U = 407.1$ J.

Figure 4.10. The black 3D curve represents the potential energy stored in cable 1 that can be achieved by maintaining the condition of setting a deformation in cable 8 of 0.2 m. The projection of this curve over the horizontal plane provides feasible nullspace variables. Coordinates are $[\lambda_1, \lambda_2, U_1]$

In order to check the validity of the points to exert the desired force in the end-effector, three points of the valid line shown in Figure 4.9 are analyzed. By substituting the two extreme points and the minimum energy point of Figure 4.9 in Equation (4.1), the tension distribution is obtained. The tension distributions for each nullspace position are shown in Table 4.2.

Table 4.2. Tension distribution for each nullspace position ($\delta_8 = 0.447$ m)	
Nullspace Position	Tension Distribution (N)
(-120.1, 84.39)	[191.6, 83.1, 50.0 , 199.7, 531.4, 422.3, 280.3, 447.2]
(-12.39, 101.5)	[137.5, 72.9, 97.4, 196.2, 484.0, 434.23, 345.23, 447.2]
(161.6, 129.1)	[50.0 , 56.5, 174.0, 190.5, 407.5, 453.5, 450.0, 447.2]

Table 4.3. End-effector wrench for each tension distribution ($\delta_8 = 0.447$ m)			
Nullspace Position	Total Potential Energy (J)	Cable 1 Potential Energy (J)	End-Effector Wrench (N Nm)
(-120.1, 84.39)	412.67	18.36	[200, 0, -1470 -500, 0, 0]
(-12.39, 101.5)	407.1	9.45	[200, 0, -1470 -500, 0, 0]
(161.6, 129.1)	423.23	1.25	[200, 0, -1470 -500, 0, 0]

As can be observed in Table 4.2, the tension in cable 8 is maintained at a constant level in order to provide the desired deformation of 0.447 m. It can be checked by substituting the tension value in energy Equations (4.4) and (4.2). In bold are the maximum and minimum tension values. Table 4.3 shows that the end-effector wrench is maintained.

It can be seen also that the boundary points of the feasible line of the nullspace provide a tension value of 50 N in cable 3 (for the minimum λ_1 value) and in cable 1 (for the maximum λ_1 value). This is the minimum tension imposed for the cables.

The feasible nullspace is constrained by the linear elongation of cable 8, and the available tension in cable 1 is obtained. If higher range of tension in cable 1 is desired, one solution could be to set a less restrictive minimum tension in cable 1 or cable 3.

4.9.2. Energy Distribution of the Reconfigurable End-Effector

The example of the rigid end-effector is used to analyze the available energy in cable 1 when the elongation of cable 8 is set to a desired value. In this practical case, cables 1 and 8 have one compliant actuator each, as described in Figure 1. The structure matrix corresponding to the two grippers is:

$$J_{weight_1}^T = \begin{pmatrix} 0 \\ 0 \\ 1 \\ -0.183 \\ -0.683 \\ 0 \end{pmatrix}; \quad J_{weight_8}^T = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0.683 \\ -0.183 \\ 0 \end{pmatrix}$$

With $\mathbf{p}_1 = \mathbf{R}\mathbf{p}_1^M = [-0.683, 0.183, 0.5]^T m$ and $\mathbf{p}_8 = \mathbf{R}\mathbf{p}_8^M = [-0.183, -0.683, -0.5]^T m$, $\mathbf{L}_{11} = \mathbf{R}\mathbf{L}_{11}^M = [0, 0, 1.16]^T m$ and $\mathbf{L}_{18} = \mathbf{R}\mathbf{L}_{18}^M = [0, 0, 1.5]^T m$. Considering $F_{1BW} = F_{8BW} = 100 N$, the external wrench imposed to the end-effector is:

$$\mathbf{F}_{ext}^* = \mathbf{F}_{ext} + \mathbf{J}_{weight}^T \begin{pmatrix} F_{jBW} \\ \vdots \\ F_{rBW} \end{pmatrix}$$

Which, in this case, is $\mathbf{F}_{ext}^* = [200, 0, -1670 \mid -550, -86.6, 0] [N \mid Nm]$. With this new external wrench applied to the end-effector, the proposed method is applied by upgrading the results from the previous section due to the consideration of the two grippers. The displacement of the cable 8_A is set and fixed to 0.447 m, which corresponds to the gripper being almost closed, because the length of the side of the end-effector is 1 m. The total potential energy considering the gripper is shown in Figure 4.11 while Figure 4.12 shows the total potential energy after imposing the displacement in 8_A . The available energy in cable 1_A is $U_{1A} \in (1.25, 27.1) J$, as seen in Figure 4.13, a higher range than in the case without grippers.

Figure 4.11. Surface section that represents the potential energy of all the cables when the two grippers are attached in cables 1 and 8. The green polygon defines the region of the nullspace that provides feasible tension values in all cables. It is different from the red polygon from Figure 7 because in this case the weight of the two grippers is being considered.

Figure 4.12. The blue 3D curve represents the potential energy stored in all cables that can be achieved by maintaining the condition of setting a deformation in cable 8 of 0.447 m and two grippers hanging from cables 1 and 8.

Figure 4.13. The black 3D curve represents the potential energy stored in cable 1_A by maintaining the condition of setting an elongation in cable 8 of 0.2 m and two grippers hanging from cables 1 and 8.

While the wrench applied to the end-effector by the cables is constant and the position of the gripper of cable 8 is fixed, the gripper of cable 1 can move in the range $\delta_1 \in (50, 232.8)10^{-3}$ m. The aperture of this second gripper can be set by imposing the corresponding values in the nullspace.

4.9.3. Open gripper

In Figure 4.14, the position of the gripper of cable 1 is set by imposing different values of available mechanical energy from actuator 1. As seen, the gripper initial position is obtained when the actuator provides 1.25 J in order to impose the minimum tension in the spring K_A that makes it work inside its linear region. In this section the effect of the closed gripper is not analyzed. Different responses are obtained by considering different values of spring stiffness. Those results are obtained by the application of Equation (4.37) with the boundaries defined by Equations (4.38) and (4.39). As observed in Figure 4.14, for a spring of $K_A = 1000$ N/m, the gripper range of motion is from 50 to 232.8 mm.

Figure 4.14. Feasible region of the energy imposed by actuator 1 for setting the position of the gripper attached to its compliant actuator. The range of feasible energy imposed by the actuator is related to the tension range available in the springs. Four different spring stiffness were analyzed for cable section 1_A . Boundaries were applied for the case of $K_A = 1000 \text{ N/m}$

4.9.4. Closed gripper

In this case, the effect of the closing gripper, which, in this case, appears when the gripper closes 0.16m from the initial state ($L_{21} = 0.16 \text{ m}$), is analyzed. Those results, shown in Figure 4.15, are obtained by using Equations (4.41) and (4.42) with the same boundaries as the previous example defined by Equations (4.38) and (4.39).

Figure 4.15. Feasible region of the energy imposed by actuator 1 for setting the position of the gripper attached to its compliant actuator without closing the gripper (black line) and with the gripper closed around a rigid solid (blue line). Four different springs were analyzed for cable section 1_B . The contact was produced at 30 J, or $L_{21} = 0.16 \text{ m}$ (green line), and consequently, the gripper was determined to be closed. Boundaries were applied for the case of $K_B = 1000 \text{ N/m}$.

4.9.5. Gripper force analysis

Once the gripper is closed, the energy method allows the force that the gripper is exerting to be measured. The results shown in Figure 4.16 show the relationship between this force and the energy of the actuator. Those results were obtained from Equation (4.43) and the force boundaries were defined by Equations (4.44) and (4.45).

Figure 4.16. Feasible region of the energy imposed by actuator 1 for exerting force on the gripper attached to its compliant actuator. Four different springs were analyzed for cable section $\mathbf{1}_B$. The boundaries were applied for the case of $K_B = 1000 \text{ N/m}$, where the range of feasible force is $F_{1BA} \in (0, 72.8) \text{ N}$.

4.10. Simulated results

4.10.1. Rigid Solid End-Effector

In order to check the validity of the method and the theoretical results, a CDPR was modeled by using the multibody dynamic software MSC ADAMS. The robot has been modeled with the same dimensions, positions, and requirements imposed in the previous section. In this model the cable mass is included, and friction effects, pulley dynamics, and a linear spring are attached between the cables and the end-effector. Figures 4.17 and 4.18, and Table 4.4 show, in detail, the structure, size, and forces applied.

Figure 4.17. Dynamic multibody model tested in MSC ADAMS. Table 4 defines the robot dimensions and configuration. Cables are actuated by pulling from their ends situated in the basement. Those cables have to pass around two pulleys, one situated in the pillar base and the other in the top of the pillar.

Figure 4.18. Dynamic model of one of the grippers. By pulling “Cable j”, the spring K_A elongates and the gripper begins to close, moving towards the end-effector. This gripper moves along a linear guide, and the secondary cable moves inside the end-effector. The pulley is designed to align this cable in a vertical way.

Table 4.4. Cable-driven robot parameters

Parameter	Value
Frame dimensions (X, Y, Z) [m]	[10, 5, 6]
End-effector mass [kg]	150
Gripper mass [kg]	10.2
End-effector center position (X, Y, Z, R, P, Y) [m, rad]	[7, 4, 1.5, 0, 0, $\frac{\pi}{6}$]
External wrench ($F_X, F_Y, F_Z, M_X, M_Y, M_Z$) [N, Nm]	[200, 0, -1470, -500, 0, 0]

A tension planner was defined with the end-effector fixed in its position. By fixing the end-effector, this analysis focused only on forces acting on the robot. In real experiments, position control must be performed to maintain the desired position.

The tension planner goes from the nullspace point where cable 1 has minimal energy until the nullspace point that provides maximal energy to cable 1. This trajectory can be observed in Figure 3.13. Figure 4.19 shows how the tension in cable 1 increased from the minimum tension, that is 50 N, until 182.4 N. The maximum desired tension was 191.6 N. This error in the maximum tension of 9.4 N could have come from the weight and inertia of the cables, which were not taken into account.

Figure 4.19. Tension in cable 1—from 50 N to 182.4 N

Figure 4.20 shows that the elongation of cable 8 m varied from 0.448 to 0.451 m. The desired elongation was 0.447, so the dynamic experiment showed a small reduction in this elongation that could be produced by the cable weight and inertia.

Figure 4.20. Elongation of the spring situated between cable 8 and the end-effector. The value oscillates between 0.451 and 0.448 m after the stabilization of the measure.

The resultant forces in the end-effector, shown in Figure 21, demonstrate that the end-effector is maintained under the desired forces, even when the additional two conditions have been set in cables 1 and 8. The measured force in the Z axis should be zero, because the desired force in this axis is equal to the end-effector weight.

Figure 4.21. Forces acting on the end-effector. A) Force in the x-axis from 215 to 199 N. B) Force in the y-axis from 5.75 to -12 N. C) Force in the Z axis from -22.8 to -13.3 N.

4.10.2. Reconfigurable end-effector

In the previous subsection, the results from the energy distribution along the eight cables of the CDPR were obtained to set the desired values of tension and deformation in the redundant cables. In this subsection, those results are used to set the desired values of the gripper to determine its aperture range and the current position that corresponds to the energy consumed by the corresponding actuator.

Figure 4.22 shows the aperture of the gripper (value L_{21}) considering Equation (4.37) along all values of actuator energy. The green region is the region where the gripper is not closed yet. It is observed that the error between the experimental and theoretical results increases after closing the gripper.

Figure 4.23 shows the displacement of the cable in the actuator in comparison with the energy of the actuator when the gripper is already closed. This displacement increases the potential energy of both springs of the compliant mechanism of the cable. Knowing this displacement, it is possible to determine the energy or force applied to the object grasped.

Figure 4.24 considers both behaviors: the opened and closed gripper.

Figure 4.22. Comparison between the theoretical and simulated gripper aperture (measuring the value of L_{21}) and the energy of actuator 1. At 30 J or 0.16 m, the gripper closes, increasing the error between the theoretical and simulated results.

Figure 4.23. Comparison between the theoretical and simulated actuator displacement compared with the actuator energy when the gripper is already closed.

Figure 4.24. Comparison between the theoretical and simulated displacement of the cable in the actuator when the gripper is open or closed by considering the two different expressions.

4.11. Discussion

The actuation redundancy of parallel robots allows to increase the workspace and the performance, and in this case, it allowed to perform secondary tasks when desired. The new perspective proposed in this article is a potential method of energy analysis that considers spring deformation, cable tension, and weights. A close-form equation was developed to relate the potential energy of each cable or the total potential energy with the nullspace that characterizes the redundancy effect.

The two appendices describe the analysis of the closed-form equation of the energy in order to demonstrate that the potential energy values along the nullspace maintain the same topology for any wrench or position value.

The theoretical and simulated results of the selection of desired tension and deformation were compared in two different cables maintaining the same wrench on the end-effector. The simulated results show that the tension applied to the end-effector and the deformation of the springs was slightly lower than the theoretical value. This error could be due to the weight and inertia of the cable, which are not considered in the energetic model. Those parameters take a portion of the energy provided by the actuators. Future work could analyze this effect in order to develop a more detailed expression of energy. Those results allow to accomplish the proposed objective 2.

Wrench variations in the end-effector when the nullspace values vary are low enough to be handled by one of the well-known position controls of parallel robots. In this article, an analysis of the energy distribution

along the cables is performed by fixing the position of the end-effector. In this way, wrench errors are analyzed without the perturbation of variations of the Jacobian matrix.

The second part of the chapter describes a mechanism based on previous results. This mechanism substitutes the rigid body of the previous end-effector to perform grasping tasks with r grippers. Gripper movement is related to the spring deformation of the rigid end-effector, and gripper force is related to cable tension. A novel cable routing design allows to actuate this secondary end-effector without the need of any sensor as in the chapter 3, fulfilling the objective 1.

Some upgrades of the usual Jacobian matrix have been developed to include the effects of the additional grippers' weights, whose effect on the main body of the end-effector varies with the orientation of the mechanism. The comparison between the theoretical and simulated results shows that the method for measuring the gripper's position by using energy is mainly suitable for those applications where the end-effector cannot have any kind of sensor or actuator that is able to provide us with a valid measurement. Some of those scenarios could be underwater environments, extreme temperatures, and emplacements like fires or outer space. This fulfils the objective 3 and validates the hypothesis proposed in this chapter.

In future research, it could be interesting to consider the relation between the energy of the actuators and the position/force of the grippers in order to make an energy-based control as seen in (Fantoni et al., 2000). This approach could also allow us to obtain a better vision and to help us to design and control hyper-redundant elastic parallel robots by imposing as many additional conditions in cables as degrees of redundancy that the system has. Also, it would be interesting to conduct visual feedback from outside the workspace to close the control loop of the gripper (Martinez-Martin & Del Pobil, 2019), reaching more complex grasping processes.

5.DIMENSIONAL SYNTHESIS

5.1.- Introduction

Some of the main disadvantages of CDPR are the inability to push a load with a cable because it bends without resistance when it is under compressing effort and the appearance of vibration of cables due to their flexibility and low inertia. It is demonstrated in (Diao & Ma, 2009) that the contribution of the vibration of the end effector due to the transversal vibration of the cable is less than the 2% compared with axial vibration that has more than 98% of contribution.

An adequate control algorithm can avoid cable sagging when the wrench applied to the end-effector allow different tension distributions in all the cables, as seen in chapter 2. If the robot is redundantly constrained and it has more actuators than degrees of freedom, different set of tension configuration can be applied in the cables to achieve the same wrench in the end-effector. These additional freedom eases the restriction of positive tension in cables (P. Liu & Qiu, 2015). On the other hand, The vibration problem can be faced with an appropriate cable dynamic model (Diao & Ma, 2009) for controlling the robot considering singular perturbation approach (M. a Khosravi et al., 2014).

Those CDPR undesirable effects require improved control algorithms, however an appropriate design of the structure is highly recommended (J-P Merlet, 1999). With geometry optimization, it is possible to optimize different performance indices, which improve the behavior of this kind of robot in order to reduce the complexity of control algorithms, achieve performance requirements fulfillment and avoid actuators and structure oversizing. One of the most important performance indexes is cable tension (Shiang et al., 2000)(Oh & Agrawal, 2005), which is directly related with the force that actuators have to exert. There are several ways to consider this magnitude. The most common optimization method for tensions in redundant cable robots is to consider the minimum tension, which satisfies equilibrium equation and restriction of positive tension (Clément Gosselin & Grenier, 2011). This optimization can be expressed as:

$$\begin{aligned} & \min_{\boldsymbol{\tau}} \|\boldsymbol{\tau}\|_2 \\ & \text{Subject to: } \mathbf{A}\boldsymbol{\tau} = \mathbf{W} \\ & \text{with } \boldsymbol{\tau} > \boldsymbol{\tau}_{min} \end{aligned} \quad (5.1)$$

Considering (5.1) it is possible to set the minimum 2-norm of the set of cable tension that satisfies the equilibrium of forces between the cables and the wrench applied on the end-effector. In addition, By using the benefits of the actuator redundancy it is possible to set a tension distribution in a secure configuration far from the configuration where any cable slacks and assuring the continuity in tension values of cables, reducing the vibration by imposing smooth reference tension values (Borgstrom et al., 2009)(Barroso et al., 2018).

However, in the case of redundantly constrained CDPRs, if the synthesis is performed by considering a minimized 2-norm of the tensions, those robots will be designed to be controlled in that specific tension condition, that could correspond to the minimum feasible tension for one or more cables. Redundancy provides the possibility to select another tension configuration with bigger (or equal) tension values. This capacity to select the tension configuration should be taken into account in the optimization process. In this way, it is possible to set configurations far from those where any cable slacks as seen in (Borgstrom et al., 2009) and also it is possible to ensure tension continuity when the end-effector is moving. These secure values are considered also for relating the actuators size with the optimum robot dimensions. For those reasons, this secure tension distribution will be one aspect to consider in this synthesis.

Besides the secured tension consideration, another objective is to maximize the amount of possible tension configurations in cables for each position and wrenches exerted on the effector. The more tension configurations are allowed for a specific pose, the further the system is from a configuration with sagging cables as well as the more control possibilities it has. The size of the space that holds these different tension configurations is measured with the null-space of the structure matrix of the system (Cetin et al., 2016), as analyzed in detail in previous chapters. The tension configuration of the system considering the freedom that redundancy provides can be expressed as:

$$\begin{aligned} & \boldsymbol{\tau} = \mathbf{A}^\dagger \mathbf{W} + \mathbf{N}(\mathbf{A})\boldsymbol{\lambda} \\ & \text{with } \boldsymbol{\tau}_{min} < \boldsymbol{\tau} < \boldsymbol{\tau}_{max} \end{aligned} \quad (5.2)$$

Where $N(A)$ is a $(m \times r)$ matrix representing the nullspace of the structure matrix, λ is the $(1 \times r)$ vector that defines the tension configuration. m is the number of actuators; n is the number of degrees of freedom and $r = (m - n)$ is the degree of redundancy of the system.

Vibration appears due to cable elasticity and the stiffness of the end-effector provided by entire set of cables in tension. An appropriate synthesis of the rigid frame is thereby needed to control the influence of these vibrations by varying the position of the pulleys and anchor points. Rigidity and elasticity of the system could be a useful index due to it has already studied its variation along the workspace as in (Z. Cui, Tang, Hou, Sun, et al., 2019), where the constant stiffness space of a CDPR is found. Natural frequency of the system could be another index upon considering masses and inertias. This vibration can be analyzed in each Plücker axis of the end effector in a similar way as the applied for Stewart-Gough platforms (Lv et al., 2010). This parameter also provides a useful measurement about the distance of the end-effector to a singular point, that usually is provided by the condition index (Voglewede & Ebert-Uphoff, 2005).

The steps followed to achieve the optimal configuration for the desired application of simulate the underwater environment requires an iterative process, as shown in Fig. 5.1. The first step of the method is the selection of the parameters whose values are desired to find. The proposed application is based on taking advantage from the actuator redundancy to exert secondary tasks to exert underwater efforts to additional limbs. The main parameters commonly needed to perform a dimensional synthesis are the frame size and the end-effector size. In this analysis, attaching points analyzed in (Marc Gouttefarde et al., 2015) are considered because they are already optimized in base of the torque exerted by the end-effector and the cable collision avoidance. The selected parameters for this research are the three dimensions of the fixed frame, the size of a cubic end-effector and the cable stiffness. The dimension of the parameter space will be equal to the number of those selected parameters.

In order to have a wide range for the secondary tasks, a big feasible nullspace region is needed. For this reason, its shape and size of the region of feasible tension distribution is also selected as an index. Maximum tension is important for applications that have elastic components, like the springs attached in series to the cable. Minimum and maximum tension is defined by the transition between the elastic and plastic state of the springs, which is defined in this synthesis problem as 20N and 800N. Due to the necessity to move inside the feasible nullspace region, other indices are the maximum secure tension, as well as the size of its surrounding available nullspace, in the way defined by (Kraus, Miermeister, et al., 2015). The last index chosen is the natural frequency because it provides information about singularity proximity and important values for the control algorithm.

In this particular application, the geometric center of a 150Kg end-effector are required to be moved inside a workspace with a shape of a 2-meters side cube close to the ground as defined in Fig. 5.6.

Figure 5.1. Scheme that define the steps to follow in the Parameter Approach method. Parameters and Indices are selected and a visual inspection is performed to know the indices values and their distribution inside the workspace. Requirements and the volume of analysis is set after the visual inspection and the parameter space representation allow to see clearer the robot performance with different sizes and stiffness. After the iterative process to select the feasible requirements, the optimization of the parameters provide the optimal solution.

5.2. - Related Work

The design of CDPR is considered more challenging and time-consuming than their analysis. This is because different analysis methods have to be included inside the design algorithm and define the specifications of structure, geometric and dimensional parameters that fulfil the required properties of the robot. Many efforts have been done in design processes. A representative number of publications are shown in table 5.1. In this table “Interval analysis” method include also those analysis along the workspace’s grids that doesn’t handle the spatial sample size, considering them as a particular case of this method.

Table 5.1. Literature about design of CDPR

Reference	Method	Objective
(Pott et al., 2005)	Interval analysis	WFW / dexterity
(Marc Gouttefarde et al., 2008)(Lamine et al., 2016)(Azizian, 2012)(Lafourcade & Llibre, 2003)(Tang et al., 2012)(Fang, 2005)	Interval analysis	WCW
(Tobias Bruckmann, Mikelsons, Brandt, Hiller, et al., 2009)	Interval analysis	WFW / specific tasks
(Marc Gouttefarde et al., 2015)	Gradient-based optimization	WFW / CoM distance
(Gagliardini, Caro, Gouttefarde, et al., 2015)	Dijkstra’s algorithm	Reconfiguration, stiffness
(Williams & Gallina, 2002)	Interval analysis	Wrench generation / collisions
(Fattah & Agrawal, 2002)(J. Pusey et al., 2004)	Interval analysis	WFW / Global Condition Index
(Pham et al., 2004)	Simplex	WFW / Stiffness
(Hassan & Khajepour, 2006)	Bounded search algorithm	Homogeneous tension distribution
(Aref, Taghirad, et al., 2009)	Visual inspection / Genetic Algorithm / Pattern Search	WFW / Dexterity / collisions
(Tang et al., 2012)	Interval analysis	ACTDI / GTDI
(B. Y. Duan et al., 2009)	Genetic Algorithm	Twisting stiffness
(Yangmin Li & Xu, 2006)	Genetic Algorithm	WFW / dexterity / stiffness
(Fahham & Farid, 2010)	Genetic Algorithm	Trajectory time /
(Jiang et al., 2011)	Least Square-Support Vector Regression (LS-SVR)	WFW
(Bahrami & Bahrami, 2011)	Genetic Algorithm	WFW / dexterity / energy
(Ouyang & Shang, 2014)	Grouped coordinate descent (GCD)	WFW
(Nguyen et al., 2014)	Unknown	WFW / collision / velocity / acceleration
(Rosati et al., 2011)	Adaptive cable-driven systems	Dexterity
(Gagliardini, Caro, & Gouttefarde, 2015)	Genetic Algorithm	Twist feasible workspace
(Gagliardini et al., 2014) (Ugray et al., 2007)	Global Search Algorithm	Compactness
(B. Gao et al., 2012)	Unknown	Actuator force
(Alikhani et al., 2011)	Geometrical approach	End-effector wrench

*ACTDI = All Cable Tension Distribution Index

* GTDI = Global Tension Distribution Index

The design methodology used is the parameters space approach (J-P. Merlet, 2005) based on multi-criteria (Hao & Merlet, 2005), taking advantage of the modularity of this kind of robots that allows fast and easy structure modifications (Jean-Pierre Merlet & Daney, 2007). In this method, a α -dimensional space called parameter space is defined. Each one of the α dimensions of this space corresponds to a design variable. In this way, each point α is a specific geometry of the structure of the robot. The β requirements that the robot must fulfill are R_i with $i = 1, \dots, \beta$. They define β regions of where the requirements are satisfied: Z_i (with $i = 1, \dots, \beta$). In order to set the requirements in an appropriate way, a visual inspection is done before the parameters space approach. It provides a quick idea of the values and distribution of the performance indices before imposing the requirements and setting the analyzed workspace (Q. J. Duan & Duan, 2014). Finally, the subspace that satisfy all the requirements is defined by the intersection of all Z_i .

An structure synthesis of a suspended cable driven robot has been made in (Marc Gouttefarde et al., 2015) considering wrench feasibility of the robot, collision-avoidance and maximum distance from the geometric

center of the end effector and its center of mass. The structure geometries, both frame and end effector, should be parallelepiped taking in account those mentioned requirements. The present analysis comes from those structure results from (Marc Gouttefarde et al., 2015), which define the polygonal shape, to provide a dimensional synthesis of the three dimensions of the fixed parallelepiped, the size of a cubic end-effector and also the rigidity of the cables that are set by using springs attached to them (X_{dim} , Y_{dim} , Z_{dim} , L_{dim} and k). As it is said in (J-P. Merlet, 2005): “*a robot with an a-priori more appropriate mechanical structure but whose dimensions have been poorly chosen will exhibit largely lower performances than a well dimensionally designed robot with an a-priori less appropriate structure*”.

Several geometric optimizations of full constraint cable robots can be found. These types of cable robots have pairs of cables in opposition with respect to the end effector or at least a force component of a cable can compensate another cable. Having such configuration, they have more possibilities for tension configuration of the cables and are not limited by a maximum vertical force due to gravity. In (Gagliardini, Caro, & Gouttefarde, 2015), actuators and winches are dimensioned considering the cable collision workspace, Twist Feasible Workspace (TFW) and the Wrench Feasible Workspace (WFW). A multi-criteria analysis is done in (Nasr & Moosavian, 2015) considering free cable collision workspace, non-singular workspace, sensitivity, stiffness and actuator wrench and optimizing with a cost function and different weights and performance indices. (Aref, Taghirad, et al., 2009) also uses visual inspection and cost function optimization for force feasible dexterous and collision-free workspace. In (Filipović & Kevac, 2018), actuators are chosen from market catalogues to select the desired workspace. In (Alikhani et al., 2011), the actuators are sized attending to the tensions, workspace and end-effector forces in a large-scale robot. (Dekker et al., 2006) shows the design analysis of a high-speed robot focusing on the workspace, accelerations and tension.

Considering suspended CDPR optimization (Lamaury et al., 2012)(J. Merlet, 2012), as done in this analysis, a dimensional and structure synthesis made using maximization of the distance from the center of mass of the end effector from its geometric center can be found in (Marc Gouttefarde et al., 2015). In (J. Pusey et al., 2004) different geometries and proportion between the end effector and fixed structure are set in order to maximize dexterity and average workspace. In (Lamine et al., 2016), interval analysis is used for the dimensional synthesis attending to the tension and workspace. In (Fattah & Agrawal, 2005), the workspace and the global Condition Index are optimized for a suspended planar robot. In (Riehl et al., 2010), cable characteristics are found attending to the tension while the layout of the redundant limbs is optimized to reduce cable tension in (Hassan & Khajepour, 2008a).

5.3. – Hypothesis and objectives

The main objective is to perform a dimensional synthesis for a suspended CDPR able to exert secondary tasks, as defined in chapters 3 and 4, in an efficient way. This will allow a high-quality simulation of the underwater environment. The geometric configuration is based on previous synthesis that shows the parallelepiped structure as the most efficient for wrench feasibility and collision avoidance. The novelty of this analysis is the application of parameters space approach methodology to increase the range of secondary tasks and their safe execution. The intended application is to handle secondary tasks as proposed in (Rodriguez-Barroso et al., 2018) with a cable modeled as a linear spring with the same stiffness value as the spring attached to the end-effector.

The indices considered are:

1. Natural frequency.
2. Secure tensions in cables.
3. Size of the feasible nullspace.
4. Shape of the feasible nullspace.

In order to define the analyzed workspace and the optimization rates, a previous visual inspection of the variation of the indices is performed to have a first idea of their magnitude. In this way, it is possible to define the parameters boundaries and the shape that the restriction manifold should have to assure a desired performance.

The execution of secondary tasks can be performed by using the actuator redundancy of the robot. A demonstration of this ability is demonstrated in chapter 3 while one application of this capability is found in chapter 4, where a gripper is controlled by using the CDPR actuators situated outside the workspace. For this sort of applications, a wide feasible nullspace area is necessary as well as a good setting time and structure stiffness.

Main chapter’s objective:

1. Define the size and shape of the end-effector and the rigid frame as well as the stiffness of the springs that will be used to fulfill the requirements imposed in chapter 1.

Main chapter’s hypothesis:

1. The proposed indices will provide their optimum performance values in the center of the frame of the CDPR because it seems to be the region where all cables work with balanced tensions distributions.

5.4. - Indices Selection

The four indices chosen allow to define the five parameters of the robot to make it more suitable for the application of the secondary tasks by using a passive reconfigurable end-effector. The natural frequency is related with the dexterity and singularity proximity (Voglewede & Ebert-Uphoff, 2005) so a high value is desired to ensure a precise and fast control. The secure tension value and the secure tension area define a safe region where the tension configuration can be modified in order to exert secondary tasks minimizing the cable failure risk. In the same way, the area moment of inertia and its area are related with the range of motion of this secondary movement.

A previous inspection analysis of a workspace performed before the iterations analyzes the indices distributions along the workspace for two different configurations in order to have a qualitative idea about the position and the volume of the desired index along the workspace to have a previous quantitative idea of the feasible restriction values. This information should be merged with the task requirements in order to take advantage of all the capabilities of this kind of robot.

5.4.1.-Natural frequency

Despite the common use that the condition index has in the dexterity analysis and its relation with the proximity to singularities that index has not clear physical meaning, as pointed in (Voglewede & Ebert-Uphoff, 2005). In that article, Voglewede et Al., show different indices with clear physical meaning on how close a pose is to a singularity considering several measures.

Due to the cables elasticity and the springs attached to them, the system uses to have a lower natural frequency than a parallel robot with rigid links. The robot natural frequency provides a measure with a physical meaning of the behavior of the end effector and its proximity to a singular configuration. This magnitude is related to the linear stiffness of the cables so that, by considering this measure as an index, it is possible not only to select the frame and end-effector dimensions but also the springs stiffness. If the end effector has a position close to a singularity, the natural frequency evaluated in the worst direction of the 6-D space is close to zero so frame dimensions are selected for avoiding those singularities and improve the dexterity. The selection of the minimum natural frequency as a performance index requires that the measurement in a singular configuration is zero and positive value in a non-singular configuration. These requirements can be fulfilled by setting the following expression (Voglewede & Ebert-Uphoff, 2005):

$$\omega_{min}(\chi) = \begin{cases} \min & \mathbf{l} \mathbf{K} \mathbf{l} \\ \text{subject to} & h_1 = \mathbf{l} - \mathbf{J}(\chi) \dot{\chi} = \mathbf{0} \\ & h_2 = \dot{\chi} \mathbf{M} \dot{\chi} - 1 = 0 \end{cases} \quad (5.3)$$

In (5.3), the minimum value of the natural frequency of the end-effector is analyzed in the six axes of the space. The actuators stiffness is represented by the parameter k (5.4). $\mathbf{M}$ is the inertia matrix of the end-effector considered from its geometrical center:

$$\mathbf{k} = \begin{bmatrix} k_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & k_8 \end{bmatrix}_{8 \times 8} \quad (5.4)$$

$$\mathbf{M} = \begin{bmatrix} m \mathbf{I}_{3 \times 3} & 0 \\ 0 & (\mathbf{R}^T \mathbf{I} \mathbf{R})_{3 \times 3} \end{bmatrix}_{6 \times 6} \quad (5.5)$$

Because the natural frequency is being considered in the end effector, cable stiffness has to be considered from the task space point of view by using the Jacobian matrix and applying the homogenization defined in (Nguyen & Gouttefarde, 2014), as:

$$\mathbf{K} = \mathbf{J}^T \mathbf{k} \mathbf{J} \quad (5.6)$$

The aim is to minimize the cost function value from (5.3), which is denominated velocity of potential energy in (Voglewede & Ebert-Uphoff, 2005). The first restriction is linear and relates the actuator speeds with the end-effector twist. The second restriction is quadratic and imposes a constant value for the kinetic energy. In such manner, the minimum value of potential energy velocity in the worst axis will give the minimum natural

frequency for that position of the end effector. The relationship between (5.3) and the equation of natural frequency of a system is demonstrated in (Voglewede & Ebert-Uphoff, 2005):

$$(K - \omega_n^2 M)\chi = 0 \quad (5.7)$$

It is necessary to set a scalar value to evaluate how appropriate this index is for the robot synthesis. This means that for each set of design variables, just one index related with the natural frequency is evaluated. So that, a region inside the workspace (Q. J. Duan & Duan, 2014) is defined where the desired requirements have to meet.

Two cases are analyzed using visual inspection in order to observe the values and distributions of the natural frequency. Two main results are expected to know: the qualitative values of those regions that are going to be analyzed and the quantitative values related with the chosen parameters. These parameters have been chosen in order to have a first idea of the performance values magnitude. The first case shows the minimum frequency for a frame with a size of 10 x 10 meters of area and a height of 6 meters with a rigidity of the springs of 10⁴N/m (10DaN/cm). The second case refers to the size of the area is 10 x 5 meters. The effector is considered in this inspection as a solid and homogeneous cube of 1-meter side and 150 kg with its sides parallel to the frame sides.

Fig. 5.2 shows the minimum natural frequency for any end-effector position inside the fixed frame maintaining the orientation. Values are shown in four layers at different heights for visualization purposes two different frames of 6-meter height have been considered: one with a base of 10 x 10 meters and the other with a base of 10 x 5 meters.

It can be seen that in this case, where the end-effector position varies along the workspace, the lowest values of natural frequency appears when the effector is situated at high altitude respect the ground. The closer the robot is to singularity, the lower the value of the natural frequency is, as it is defined in eq. 5.8. Indeed, because the optimization problem has been solved as an eigenvalue problem the corresponding eigenvectors show the minimum natural frequency direction of the end effector in Plücker coordinates.

Figure 5.2. Values of the minimum natural frequency(rad/s) calculated in five different heights (0.5, 1.5, 3, 5 and 5.7 meters) for 2 structures with distinct dimensions and values of rigidity of the springs. Distance between black lines is 0.5 rad/s

5.4.2.- Secure tension

The maximum torque that motors can apply is an important condition that can be imposed in the dimensional optimization process. Tension is a basic index for optimization of all kinds of CDPR (Aref, Taghirad, et al., 2009)(Marc Gouttefarde et al., 2015)(Nasr & Moosavian, 2015). In the case of redundant robots, there are many tension configurations that provide the same wrench in the end effector, as observed in (5.2). The nullspace of the Jacobian Matrix transpose is used to consider the additional cables effect. This shows how different values of τ can be chosen when lambda takes values different to zero.

The usual and agile way for considering a tension scalar value for the optimization is:

$$\tau' = \max (\mathbf{A}^+ \mathbf{W}) \quad (5.8)$$

This equation shows a scalar tension value for the optimization. This value allows the end-effector to be in a certain position with the minimum set of tension. Moore-Penrose pseudo inverse guaranties that the tension set that provides the end-effector desired wrench is the one that has minimum 2-norm. It is thereby enough for the actuators to exert a torque able to impose the maximum required tension for this tension set. However, the use of the Euclidean norm takes in account positive and negative values of tensions in order to achieve minimization and that is physically impossible for a cable that cannot push the effector. In addition, there is another drawback in the use of this method because taking the minimum set of tension configuration does not consider the capability that the redundancy configuration provides in the selection of cable tensions.

In order to solve both problems related with the use of the Moore-Penrose pseudo inverse, a particular solution of the cable tension vector (τ_p) is considered. The general solution of the tension vector is formed by this particular solution (τ_p) and the homogenous solution (τ_h) obtained by using the null-space of the transpose of the Jacobian matrix, (5.2):

$$\tau = \tau_p + \tau_h \quad (5.9)$$

The lambda vector values provide all possible cable tension configurations. It has to be considered that a cable can only exert positive tension so that, the lambda domain is restricted by a boundary defined by those configurations where a cable reaches the minimum or maximum tension. In (Mikelsons et al., 2008), a method for calculating the boundary within which a feasible tension solution can exist is proposed. An example for this region is represented in Fig. 5.3.

The available nullspace shape region depends on the Jacobian matrix, the wrench applied on the end-effector and the tension limit imposed in all cables. In order to have an idea of the shape and values of this space, a robot with dimensions of 10x10 meters of base and 6 meters height is considered. The end-effector is situated in the position $X_1 = X_2 = [-3, 2, 3]$ meters considering $[0, 0, 0]$ as the point situated in the center of the base in the floor. In the first case, the wrench applied in the end-effector is $\mathbf{W}_1 = [1000, 0, -1470 | 0, 0, 50]$ (N | N·m) and in the second case, the wrench applied is $\mathbf{W}_2 = [0, 1000, -1470 | 0, 0, 0]$ (N | N·m). The vertical wrench corresponds to a weight of 150Kg. The torque component is applied at the cube geometric center. The minimum tension is set to 0N and the maximum at 1100N in order to have an illustrative example of this concept.

Figure 5.3. Representation of the null-space constrained by the maximum and minimum force that is possible to apply in the end-effector. Black polygon corresponds to the region where tensions higher than the minimum value are applied while red polygon corresponds to those tensions lower than the maximum allowed value. The intersection of both, blue polygon, provides the feasible tension configuration.

Figure 5.4. Values of the maximum secure tension (N) calculated in four different heights (0.5, 1.5, 3 and 4 meters) for 2 structures with different dimensions and a cubic end-effector of 1 side. White values correspond to maximum tensions outside the tension boundaries imposed as $[20, 800]N$

In Fig. 5.3, the $\mathcal{J}'$ null-space feasible region, where the lambda values can move to provide a valid tension configuration is shown. This region varies with the end-effector pose and the applied wrench. When any of these conditions are modified, the region changes and it is necessary to recalculate. The calculation of the region can be done by using interval analysis based on numeric methods or an algebraic analysis.

For this analysis, the required tension value to conform the corresponding Z_i subspace is the maximum value of optimally secure tension vector defined in the way of (Borgstrom et al., 2009). Secure tension sets are far from those configurations where any cable slacks or reach maximum tension. All cables thereby provide continuous values of tension during the movement of the end effector far from tension boundaries. In addition, secure tension creates a tension margin to handle any external effort applied in the end effector or any contact with the environment that modifies the wrench applied. This secure tension value is obtained when the barycenter of the feasible nullspace polygon is considered (Blue point in Fig. 5.3). This method can also provide tension configurations that cannot be reached by using just Moore-Penrose pseudoinverse, an example is considered in the case 1 of Fig. 5.3 where the cable tension is set for a value of zero lambda but that configuration does not fulfill the restriction of minimum tension. Considering the point situated inside the black polygon, it is possible to set another tension configuration inside the maximum and minimum boundaries.

The robot requirement related with the cable tension can be chosen as the tension value of the most tightened cable. In this manner, the actuators can be dimensioned with this value, that is higher than the values provided by using the Moore-Penrose pseudoinverse, however the tension configuration ensures continuity of the tension without reaching boundaries. The secure tension values in case 1 are: $\tau_1 = [656.2, 652.5, 21.2, 60.2, 19.8, 62.9, 746.2, \mathbf{1036.5}]$ and in case 2 are: $\tau_2 = [899.7, \mathbf{905.6}, 217.5, 258.9, 313.3, 344.9, 449.3, 605.6]$ (Higher values in bold).

The scalar value corresponding to this index is chosen as the maximum value of the optimally secure tension. A volume is defined in the same way of the previous epigraph to obtain the maximum tension value of different positions inside the 2-meter cube.

A visual inspection of the maximum secure tension inside the workspace of two frame shapes is presented in fig. 5.4. In this case, the secure tension boundaries have been set to $\tau_{sec} \in [20, 800]N$ to avoid working with the maximum tension and increase the security factor.

5.4.3.- Null-space feasible region

The degree of redundancy is the number of actuators minus the degrees of freedom of the end-effector, in this case, this is $r = 8 - 6 = 2$, the nullspace polygon of feasible tension has a basis of order 2, $\Omega \subset \mathbb{R}^2$. The size of this subspace provides a measure of the amount of freedom that the robot has in order to modify its internal tension levels.

As shown in Fig. 5.3, There are two polygons that represent the regions where the tension configuration of the cables can vary modifying the value of λ_1 and λ_2 . The points situated inside the red polygon conform tension configurations that satisfy the maximum tension level condition. The region inside the black polygon represents tension configurations where all the cables have higher tension values than the minimum tension allowed. So that, the acceptable region for values λ_1 and λ_2 is the intersection in blue of the two polygons. The size of the admissible area in case 1 is 614.9 N^2 , in case 2 is 325890 N^2 .

The nullspace region is the most important index to amplify the secondary tasks effects. In one hand, the feasible nullspace, Ω , should have a wide area around the secure working point to handle external forces and those effects that can alter the tension accuracy. This area should be big enough to avoid reaching extreme tensions due to perturbations. On the other hand, Ω should have regions far from the secure working point to be able to provide the secondary tasks movements.

It is possible to size the robot by imposing this available nullspace size as two restriction indexes: In order to provide a wide safe area around the secure tension distribution a minimum safe area is imposed. In addition, the ability to execute adequate secondary tasks can be measured by the area moment of inertia of Ω whose expressions are defined as:

$$I_{\lambda_1} = \int_{\Omega} \lambda_2^2 d\lambda_1 d\lambda_2 \quad (5.10)$$

$$I_{\lambda_2} = \int_{\Omega} \lambda_1^2 d\lambda_1 d\lambda_2 \quad (5.11)$$

$$I_{\lambda_1 \lambda_2} = \int_{\Omega} \lambda_1 \lambda_2 d\lambda_1 d\lambda_2 \quad (5.12)$$

Those area moments of inertia are measured from the secure tension point. In this way, taking the value of the two principal inertia axes, by looking at the eigenvalues, a measurement of the area around the safe point is obtained instead of just the area value. The scalar value provided by this index is the minimum value of area moment of inertia of the principal axes.

The visual inspection of minimum area inertia inside the workspace of two different sizes are shown in fig. 5.5. With the information obtained from this data and seeing that the higher nullspace regions are centered and in lower regions, the points of analysis of the workspace have been taken from the volume of a cube of 2 meters like in the previous cases.

Figure 5.5. Values of the minimum area inertia of the nullspace (u^4) calculated in five different heights (0.5, 1.5, 3, 4 and 5 meters) for 2 structures with distinct dimensions

5.5.- Analyzed workspace

This volume corresponding to the analyzed workspace is chosen as a 2 meters side cube centered on the base and just over it. This will be the initial region where the restrictions must be fulfilled. The minimum values of the natural frequency are analyzed in different points inside this volume and the minimum of those values is chosen as the representative performance value for the dimension and stiffness synthesis of the robot. Fig. 5.6 shows the 27 chosen points from this volume which has been defined by considering that the task to be performed is close to the ground, where minimum natural frequency values are high and the effector is far from singularity points.

Figure 5.6. In blue are the 27 end-effector positions where the indices are analyzed in order to obtain just one performance value for each set of design variables

5.6.- Requirements

Five indices are considered for the five parameters (three frame dimensions, end-effector size and spring stiffness). These indices are: end-effector minimum natural frequency, maximum value of the optimally secure tension, size and area moment of inertia of the feasible null space.

The requirement values are selected according to the robot purpose to exert secondary tasks. Gravity is the only external force acting on the end-effector, so that, the available nullspace region doesn't vary with external forces in this analysis. In the real application, some external perturbations can be applied and modify the shape of Ω but the controller should be able to handle them by taking advantage of the secure tension configuration.

The natural frequency value can be chosen considering its relation with the maximum setting time, defined as:

$$t_e = \frac{4}{\zeta\omega_n} \quad (5.13)$$

With ζ the damping factor and the setting time defined with a margin of 2% from the desired value. This value needs to be related with the acceleration parameters from the actuators as well as their dynamic values in order to make them able to achieve handle this t_e value.

The maximum cable tension has been chosen as the tension where the spring pass from the elastic to the plastic state while the minimum is the pretension of the spring, where the spring doesn't elongate under tension. The secure tension will be always between these two boundaries to have enough margin to perform the secondary tasks and also handle unexpected effects. The value of the maximum secure tension configuration can be chosen by using visual inspection for the specified robot configurations.

The minimum area and area moment of inertia from the admissible region of the nullspace can be related to that of a circle or other polygon. This polygon set the distance from the secure tension point and the Ω boundary that can provide movement and force to the secondary body attached to the end-effector (Rodriguez-Barroso et al., 2018).

The spring stiffness is aimed to be small to make the force easier to be measured because according to (Jean-Pierre Merlet, 2014) position accuracy are less influenced than cable tension when discrete controllers are used. So that by increasing the spring elasticity, cable elasticity can be neglected and also increase the force sensitivity of the system, with the disadvantage of a lower response time and accuracy.

The initial minimum natural frequency inside the cube is set to 9.5 rad/s ($\approx 1.5\text{Hz}$). This value imposes a setting time of 0.42 seconds when the system is critically damped, $\zeta = 1$. The maximum secure tension value is set to 500N and the maximum to 800N. The minimum area moment of the admissible region of the nullspace is set as the same of a circle of radius 200mm centered on the secure tension point of the nullspace. The area moment of inertia of this circle is $I_C = \frac{\pi}{4}200^4 = 1.2566 \cdot 10^9 [N^4]$. The minimum area around the secure point is the same of a circle of radius 50mm: $A_C = 7853 [N^2]$ To avoid collision between cables, the minimum distance between them has been selected as 100mm.

All these values have been considered applying a previous visual inspection of the shape and values of the indices in different points of the workspace and with different values of the stiffness of the cables. No variation is imposed in the analyzed workspace in order to maintain fixed this requirement.

Table 5.2. *Indices requirements that need to be fulfilled in all the points defined in Fig. 5.6*

Index	Natural frequency	Secure tension	Second moment area of Ω	Area of Ω
Initial Required value	> 9.5 rad/s	< 550N	> $1.26 \cdot 10^9 N^4$	> $7853 N^2$

The optimization rates have been defined according to their relevance with the current application. The indexes corresponding to natural frequency and secure tension have been defined as relaxable while the second moment area of Ω has been set as compulsory [18].

Table 5.3. *Requirement variation in each step if no solution is achieved in the parameter space*

Index	Natural frequency	Secure tension	Second moment area of Ω	Area of Ω
Restriction variation	- 1 rad/s	+ 50N	+ 0 N^4	+ 0 N^2

As observed in table 5.3, the nullspace area is considered as the most important index so that, no variation is defined for each iteration in order to maintain the minimum feasible nullspace area moment. However, allowable secure tension is increased in each iteration as well as the allowable minimum natural frequency is reduced. Those variations make easier to fulfill the requirements and obtain valid parameter configurations.

In case of multiple solutions, the index variation for each step is shown in table 5.4, which increase the performance requirements.

Table 5.4. Requirement variation in each step if multiple solutions are achieved in the parameter space

Index	Natural frequency	Secure tension	Second moment area of Ω	Area of Ω
Restriction variation	+ 1 rad/s	- 50N	0 N ⁴	0 N ²

5.7.- Optimization rates

Once the first iteration has been done, the parameter space provides enough information to select any parameter configuration that fulfils the index requirements. However, the size of this region of feasible parameter configuration could be inadequate because it could provide no solutions or this solution space could be too large. In this case, the restrictions can be varied according to their critical importance for the application. In the same way, the analyzed workspace can be varied modifying its volume or shape where the restrictions have to be fulfilled, as seen in the method scheme from Fig. 5.1.

In case that no solution is obtained for the space parameters, the required value of each index needs to be modified in the following iteration to provide a less constrained problem. Alternatively, the analyzed workspace can be reduced. Attending to the results from the visual inspection and the desired application of secondary tasks development, the variation of those four indices in case of no-solution has to be defined in the initial stage.

In the other hand, if several solutions exist inside the parameter space, the restrictions can be increased in each step or the analyzed workspace can be increased. The last iteration of this process appears when the next iteration provides no solution in the searched range.

The result of this process is the minimum region in the parameter space that fulfils the requirements and its variations. The size of this regions depends on the tolerance and available values of each parameter as seen in the next section.

5.7.1.- Synthesis accuracy

Several analyses can be performed inside the workspace, null-space and the parameter-space to define the final optimum region. Those analyses are performed by analyzing the specific configurations, which are separated by a distance that was defined before the first iteration.

The workspace grid resolution allows to find with more or less accuracy the minimum or maximum index for one specific parameter configuration. Bigger grid size could provide index points that are far from the extreme value that is being searched. However, the time computing will be lower in that case. In the case of the nullspace, its resolution is related with the tension boundaries. Finally, the sample size inside the parameter space is related with the precision of the components of the robot like the available sizes for the modular structures in commercial catalogues.

In this analysis, the nullspace boundary is obtained by using algebraic methods, so its definition is theoretically totally accurate (assuming a perfect kinematic chain). However, the index errors that come from a poor grid definition in the workspace will produce a noise in the parameter space volumes. This noise comes from the oscillation that the error produces in the extreme index value along the parameter space. This noise will alter the shape of the volume boundaries in the parameter space, providing acceptable configurations that does not fulfil the requirements. This problem can be compensated with the iterative process that increase the requirement values when many solutions are provided. In this way, the initial set of restrictions will be further from the final feasible volume in the parameter space.

Assuming those sources of error, in order to reduce the computation time, they can be compensated in the iteration process. However, if time is not a restriction, more detailed grid can be analyzed or also the size of the boundary grid can be reduced until minimum tolerances as defined in the interval method (Alefeld & Mayer, 2000)(Jean-Pierre Merlet, 2009b)

5.8.- Results: Feasible parameter space

The four regions where each requirement is fulfilled (Z_i , with $i = 1, \dots, 4$) can be defined as shown in figs. 5.8, 5.9, 5.10 and 5.11. In those images, each scalar index is shown for each one of the 4 dimensions and spring stiffness value. The values are provided just for the *feasible parameter boxes* (FPBs) defined in (Hao & Merlet, 2005). In this way, a better knowledge of the robot performance is obtained.

The sizes analyzed are for the length of X and Y axis: 3, 3.5, 4, 4.5, 5, ..., 25 meters. For the Z axis, which is the robot height: 4.5, 5, 5.5, 6, 6.5 and 7 meters. For the spring stiffness the values chosen are: 5000, 10000, 15000 and 20000 N/m. For the end-effector side: 0.6, 0.8, 1 and 1.2. In order to increase the computational speed, no rotation is considered in the analysis assuming that in the high-quality region those will be reduced.

To make a better representation of the $\mathbb{R}^5$ subspaces that represent the region where the requirements are fulfilled, several slices are shown at different heights. Subspaces with different spring stiffness values are presented for those indices that have dependencies with this parameter, which is the minimum natural frequency. These 5 parameters are considered and tested in order to know for which parameters values the 4 indices satisfy the requirements.

Figure 5.7. Subspace Z_1 corresponding to the parameters that satisfy the requirements of minimum natural frequency for $K = 10^4 N/mm$ (left column) and $2 \cdot 10^4 N/mm$ (right column). Frequency values are in rad/s and the exterior boundary correspond

to the minimum natural frequency set as 9.5rad/s. In red are shown the parameters which corresponds to ω_n lower than the requirement. This representation corresponds to a end-effector of 1m side.

5.8.1.- Minimum natural frequency

Valid regions of parameter space that satisfy the requirement for minimum natural frequency in the end effector is presented in fig. 5.7. As seen before, the scalar index corresponding to the minimum natural frequency is obtained from the analysis made in the points shown in fig. 5.6. The stiffness value of $k = 10^3 \frac{N}{m}$ doesn't provide any valid region. It can be observed that the values of minimum resonance increase with the stiffness value as shown in (eq. 5.12).

5.8.2.- Maximum secure tension

The maximum value of the optimal secured tension use to be higher than the maximum tension value obtained from the usual tension optimization that focus on tension minimization. In this case, tension distribution obtained in the barycenter of the available nullspace is selected. This requirement is more restrict than the usual method, however robot dimensions will be chosen based on a more secure working mode.

Fig. 8 shows the maximum of $\max(\tau_{sec})$ analyzed in the points from fig. 5.6. In this way, working with a secure tension distribution, the end-effector can move inside the defined region without reaching a tension higher than 550N, without considering dynamic effects. For sizes lower than 5.5m this condition is not fulfilled.

The most relevant information from the tension analysis is that the robot has to have a minimum height/length ratio in order to keep the vertical component of the cables and to preserve the ability for exerting a force against the end effector weight.

Figure 5.8. Subspace Z_2 corresponding to the parameters that fulfill the maximum secure tension requirements. In red are shown the parameters which corresponds to τ_{sec} higher than the requirement.

5.8.3.- Minimum available nullspace and area moment of inertia

The available nullspace, Ω , is related with the possible tension configurations that provide the same end-effector wrench value. So that, its size is related with the capabilities related with the actuator redundancy like avoiding cable failure due to the higher distance between the secure tension distribution and the Ω boundary. The Ω size is also related with secondary tasks in the end effector, as defined in (Mikelsons et al., 2008), so wide areas allow larger movement ranges of the end-effector mechanism. In addition, as mentioned, this index is related with the necessity to maintain the tension continuity along different paths and for avoiding configurations that generate distensions. So that, this region has to be big enough to provide secure tensions and spread enough to be able to exert wide range secondary tasks.

Fig. 5.9 shows the index value corresponding to the minimum second moment area of Ω that also fulfils the restriction of minimum area of Ω , analyzed in the points from fig. 5.6. By imposing a lower constraint in this value, we are looking for a shape wide enough to take advantage of the redundancy effect. Since this value is independent from the stiffness value, the tridimensional projection of this subspace in any value of parameter K is identical.

Figure 5.9. Subspace $Z_3 \cap Z_4$ corresponding to the parameters that fulfills the minimum available nullspace area requirement. Values of area in N^4 and in red are shown the parameters which corresponds to I_{Ω} lower than the requirement.

5.8.4.- Optimal design values

Considering the 4 indices ($\min(\omega_n)$, $\max(\tau_{sec})$, $\min(I_\Omega)$ and $\min(A_\Omega)$) and the 5 parameters (X_{dim} , Y_{dim} , Z_{dim} , L_{dim} and k), it is possible to establish a final subspace in $\mathbb{R}^5$ that fulfills all the imposed index requirements in the parameter space. Fig. 10 shows this subspace for a fixed end-effector value of 1 meter. This subspace is represented by slices for the k and z values. It doesn't appear for z -values lower than 6m. The *valid parameter boxes* (VPBs), shown in green (first iteration) and blue (second iteration) are the intersection of the *feasible parameter boxes* (FPBs).

Figure 5.10. Subspace that fulfills the 5 requirements in the penultimate iteration (in green) and in the last iteration (in blue) represented in the parameter space. In purple is the optimal configuration after the optimization. There is no solution for $k = 5 \cdot 10^3 \frac{N}{m}$. The solution is chosen by attending to the optimization of the feasible parameters. The purple point corresponds to one valid configuration corresponding to $(X_{dim}, Y_{dim}, Z_{dim}, L_{dim} \text{ and } k) = ([8.5, 9], [7, 7.5], 6, L_{dim}, 1.5 \cdot 10^4) [m, m, m, m, N/m]$

In order to represent the 5 dimensions of the parameter space, the remaining parameter that is the end-effector size is represented in Fig. 5.11.

Figure 5.11. Subspace that fulfills the 5 requirements in the penultimate iteration (in green) and in the last iteration (in blue) represented in the parameter space when end-effector size varies.

The subspace from fig. 5.10 and fig. 5.11 has been obtained with a spatial sampling of 0.5m in each spatial axis and $5 \cdot 10^3 \frac{N}{m}$ in the stiffness axis. The requirements are fulfilled for the updated restrictions after the iterations. Those last index restrictions are shown in table 5.5.

Table 5.5. Final Indices requirements after iteration.

Index	Natural frequency	Secure tension	Second moment area of Ω	Area of Ω
Initial Required value	$> 10.5 \text{ rad/s}$	$< 500N$	$> 1.26 \cdot 10^9 \text{ N}^4$	$> 7853 \text{ N}^2$

5.9.- Discussion

Synthesis of CDPR is a complex task due to the big number of variables and considerations needed to impose. This chapter is focused on four different performance aspects considered in a novel way that are characteristic in this type of robot: stiffness, vibration, secure tension distribution and secure region and capacity to exert secondary tasks by using the redundant configuration. The requirements imposed in those indices allow using the Parameter Approach method for a suspended CDPR with 5 parameters: 3 frame dimensions, 1 effector dimension and 1 cable stiffness.

A visual inspection analysis has been performed in order to have enough information for setting the restriction values and the desired volume of analysis inside the robot workspace. This previous natural frequency inspection can be seen in fig. 5.2 that shows those regions that have higher stiffness in all the 6 end-effector axes. As seen, the base shape has a strong influence on the regions and values of this index: regular bases tend to have a low and centered region of high stiffness while rectangular bases tend to have their better performance region close to the shorter sides and in a higher region than the regular one. This is an unexpected fact that goes against the main hypothesis that considers that the central region provides the best values of all indices. However, by taking a centered region as the high-quality volume, an appropriate value of the parameters can be obtained after defining the requirements of this region. So this, the visual inspection shows that a more regular basis is more appropriated for this kind of developments. Natural frequency values also provide a quantitative estimation of the requirement to impose to the system.

The maximum secure tension is analyzed in fig. 5.4, where those values have been plotted inside the volume of two different frames. It is observed that the minimum secure tension values are obtained in the center of the base and for lower heights. The base shape doesn't seem to have a significant influence on the minimum tension regions.

The available nullspace size, which is related with its area inertia, is shown in fig. 5.5 for the visual analysis previous to the restriction setting shows also that the centered and low regions of the interior volume provide higher available nullspace areas. Some curious different shapes, are obtained for high end-effector positions when compared the regular and irregular base shapes of the frame. As seen in fig. 5.5, rectangular basis tend to have a good region for high end-effector position with a wide available nullspace.

The regions of requirement fulfillment shown in fig. 5.7, 5.8 and 5.9 provides the information of the parameters needed to achieve each index. Fig. 5.7 shows that higher natural frequency values are obtained in structures with regular base and higher structures require wider bases. So this, higher stiffness are obtained when the structure is approximately more similar to a regular cube (with a slightly lower height value). Higher cable stiffness values provide higher natural frequency values and wider available volume in the parameter space. Minimum secure tensions are obtained in tall structures. As seen in fig. 5.8, there is a monotone trend to decrease the secure tension value when the height increases. Indeed, lower base areas can be defined in taller structures, having even the possibility to design a 4.5x4.5m base when the height is 6.5m.

The third and fourth indices, the minimum area inertia moment and the minimum area are fulfilled for the major base dimensions when the frame is taller than 5m. Wider available nullspace regions are obtained for

frames with a low height-base ratio. The region in the parameter space corresponding to this index is similar to that corresponding to the natural frequency, however in this case the base doesn't need to preserve its squared shape, being possible to have shapes with very different side lengths like 12x4m for a 4.5m height frame. The end-effector size has an important influence in the indices: bigger end-effectors can exert torque with less tension but the feasible region in the parameter space is more reduced than in the case of smaller end-effectors. By merging the five indices it is observed that the dimension requirement imposed by secured tensions are opposed to the requirements for increasing the natural frequency and available nullspace area.

As conclusion, the main objective has been fulfilled by defining the appropriate parameters of the CDPR that provide the desired performance, as well as a proper definition of that performance values that could provide a high-quality simulation of the underwater environment. The main hypothesis hasn't been totally validated due to the unexpected distribution of the regions of higher stiffness for the end-effector inside the workspace of the robot: For non-squared bases, those regions are not centered but closer to the shorter sides of the base. However, this fact is not against the fulfillment of the objective and make the methodology used in this chapter useful even to handle this issue.

6.DESIGN AND BUILDING

6.1.- Introduction

The on ground underwater simulation exerted to the end-effector have previous requirement that were defined in chapter 1. Those requirements were the seed for the dimensional and stiffness synthesis performed in chapter 5 where the robot performance needs were translated into the structure requirements shown in Table 6.1. Table 6.2 show the final performance indices required after the improvement obtained by using the optimization from the dimensional synthesis of the chapter 5.

Table 6.1. *Design requirements*

$X_{dim}[m]$	$Y_{dim}[m]$	$Z_{dim}[m]$	$L_{dim}[m]$	$k\left[\frac{N}{m}\right]$	$\tau[N]$	$i\left[\frac{m}{s}\right]$
[8.5, 9]	[7, 7.5]	6	1	$1.5 \cdot 10^4$	[20, 800]	1.5

Table 6.2. *Indices performance*

<i>Index</i>	Natural frequency	Secure tension	Second moment area of Ω	Area of Ω
<i>Initial Required value</i>	> 10.5 rad/s	< 500N	> $1.26 \cdot 10^9 \text{ N}^4$	> 7853 N^2

The main components of the CDPR are: the rigid frame, the end-effector, the cable, the winches, final pulleys, electric and electronic hardware and security systems. Each part plays a specific role that has to be taken into account in the design and assembly process to perform it in an accurate and controlled way:

The rigid frame establishes the fixed points in the inertial reference frame. Those points will define all the geometry and kinematics relations with the end-effector. It is important to reduce as much as possible the deformation, vibration and undesired movements of this frame and analyze their behavior and boundaries. Due to the height required for the CDPR, the design of this structure has to focus on the rigidity establishing a robust foundation and pillars.

The end-effector is a mechanical structure whose main tasks is to maintain the positions where the cables are attached in known and fixed emplacement. It is also important to have its CoM defined and also the contact points with the environment to establish the force closure with the cable tensions. A robot with a rigid bodies structure, a human with a rigid system of anchors or a simple parallelepiped block could provide those requirements, each one by using different measurement methods specific to their nature. For the experiments developed in the designed CDPR, an initial rigid structure is designed. It is intended to have a high mass to be able to provide high tension values in the cables. The contact points are with the floor in the four corners of its basement to provide a wide equilibrium area where the projected vertical force can move without alter the static equilibrium.

The cable is the element in charge of transmit the motor effort to the end effector. It is important to characterize its dynamical behavior because it will be added to the wrench applied to the platform. In this application, where the secondary tasks play an important role, the cable stiffness is required to be maintained in a constant value with the elastic behavior concentrated close to the end-effector to actuate the secondary body. For this reason, a stiff material as the steel is chosen for the cable while the springs attached between the cable and the platform will provide the elastic value of the entire cable by neglecting the elastic behavior of the steel cable according to the expression:

$$(K_{eq})^{-1} = (K_{spring})^{-1} + (K_{cable})^{-1} \quad (6.1)$$

Where the equivalent stiffness (K_{eq}), can be chosen as the spring stiffness (K_{spring}) when:

$$K_{cable} \gg K_{spring}$$

The main task of the winches is to coil the cables in a controlled way to provide tension and position values. Due to the material of the cable, there exist a minimum bending diameter so this magnitude needs to be imposed to the winches design. In addition, they have to be big enough to coil all the amount of cable needed for the worst situation where the end-effector is in the further position from each winch. Those requirements impose a minimum size, relating the workspace size with the size of the winches. In this specific application, another requirement is imposed based on the forward kinematic: to achieve an adequate relation between the actuator's displacement and the platform movement, the amount of cable coiled needs to be directly related with the motor's encoder measurement. This can be done by routing the cable around the winch and aligning it in each turn to avoid the cable from riding on top of itself. This cable alignment also ensures that the diameter is constant in each turn, so the relationship between the motor torque and the linear force that provides cable tension will be constant.

The final pulleys are the mechanisms that ensures that the cable parts from the rigid frame to the end effector. They need to ensure the cable alignment from this exit point to the attaching point with the moving platform and have low inertia and slip factor to can obtain an appropriate model of its dynamics and avoid to increase the dynamics of the actuator.

Due to the high frequency signals handled by this robot like the vibrations from the cables or the high resolution from the encoders, a FPGA is used. One device able to work with FPGA and RT systems in an industrial-like environment is the CompaqRIO from National Instruments. This device allows to read and write signals with a minimum acquisition time of 55ns for IO digital signals (NI-9402) and a maximum sampling rate of 51.2 kS/s for analogic signals (NI-9218). For the actuators, servomotors have been considered to analyse their feasibility to the project.

Security systems are very important in this type of robot due to its high power and workspace, for this reason a security plan is required for its working and also for its building. Different emergency stop measurements are provided, security nets, light signals and breaks and secure software protocols.

6.2.- Related Work

Design and building are processes that requires a lot of time, as observed in the IPAnema project (Pott, 2018) it took around 32 person-month to perform the initial operations of the first prototype of the family. Considering the time until the first version of the industrial prototype is made, the estimated provided is 15 person-year. Very different types of specific design can be found for each component of a CDPR in the prototypes from the literature.

The winches have evolved from basic and functional mechanisms like in (Hiller et al., 2005)(Pham, Yang, et al., 2005)(Chen et al., 2012), where the cable is coiled around a grooved drum to maintain the constant radius and avoid the cable to overlap. In (Pott, Mütterich, Kraus, Schmidt, Miermeister, Dietz, et al., 2013), this system is improved by adding a cable guide that moves parallel to the drum to help it to be coiled without slack and in (Zitzewitz et al., 2009) the inertia and friction was reduced to improve the performance. For systems where more than one cable parts from the same point, a double winch is used in (Fassi et al., 2010) while in (Gonzalez-Rodriguez et al., 2017) this duty is performed by a compact winch. Double actuator systems were used to create impact efforts in haptic simulators (Billette & Gosselin, 2009).

Due to the helicoidally shape of the coiling, the rotation of the drum measured by the encoder should be related with the actual uncoiling of the cable. This expression is provided in (Pott, 2018):

$$l = n_r \sqrt{d_2^2 \pi^2 + h_r^2} \quad (6.2)$$

With n_r the number of turns of the drum, d_2 the diameter, h_r the distance between the cables in each coil and l the respective cable length.

Apart from winch-based systems, also rail-based systems are used with cables of constant length, both compared in (Tobias Bruckmann et al., 2011). A method for the design and selection of the actuators was developed in (Kraus & Pott, 2013) attending to the dynamic characteristics of the robot and the motors. Pneumatic actuators are used in (Zhao et al., 2017) in addition to the electric to simulate the neck movement.

As an end-effector, a model of a ship has been used in (Tobias Bruckmann et al., 2011) to compute the viscous flow around. For construction applications, extrusion systems are used as in (P. Bosscher et al., 2007). Sensors and cameras are used to collect data from agriculture in (Bai et al., 2019) or sport events as in (Brown, 1985).

An interesting mechanism able to relate the cable stiffness with its tension is proposed in (Yeo et al., 2013). By using these mechanisms, the tension distribution analyzed could be related with stiffness variations in the end-effector.

A novel cable routing based on cable loops is proposed in (H. Liu, 2012). In this proposal the cables are not attached to the winch and the platform but they form a loop passing through both.

6.3.- CARcinOs Prototype

To perform the experiments related with the compliant actuator, a small size prototype of a suspended CDPR is built. Performance and working details are commented in chapter 3. The size is a parallelepiped of (105, 70, 104) centimeters while the end-effector is a parallelepiped of (140, 90, 30) centimeters. The spring and the compliant actuator were described in section 2. As observed, the end-effector can be fixed in a specific position to maintain the Jacobian matrix values during experiments that requires as independent values the wrenches exerted to the end-effector.

Figure 6.1. First version of CARcinOs prototype for testing the compliant actuator from chapter 3

One of the main characteristics of this small-size prototype are the winches design. In order to have a non-expensive and basic prototype for the preliminary experiments the coiling system of the nylon cable of 0.6mm, eight M16 screws were used. As observed in figure 6.2 and figure 3, each screw is attached to a DC motor of Maxon with graphite brushes and 3 watts able to provide a torque of 2.42×10^{-3} Nm. Each motor has a reducer of 275:1, so the nominal torque provided by the actuator is 0.67Nm. A rotational encoder of 4400 counts per turn is attached to the shaft of the motor. The twist of this screw with respect its fixed nut has 1 DoF and corresponds to a linear displacement along its main axis dependent of the rotation around the same axis. This twist can be expressed as:

$$\begin{bmatrix} \dot{\theta} \\ \dot{l} \end{bmatrix} = \begin{bmatrix} 1 \\ h \end{bmatrix} \dot{q} \quad (6.3)$$

Being q the motor rotation, θ the screw rotation, l the screw linear displacement and h the screw pitch. This screw movement allows to coil the cable without crossing and maintaining the cable's diameter.

Figure 6.2. Design of the winches of CARCinos. The DC motor (g), with its gearbox and encoder attached, is screwed to its plate (c) by using two screws in its front part. This plate (c) is screwed to a moving frame (d) able to slide along a linear guide (h). The axis of the motor is fixed to a screw (e) by a coupler (f). This screw pass through a fixed nut inside the plastic piece (a), that is screwed to the fixed frame (b). When the motor turns, the screw perform a helicoidally movement able to deploy (A) or coil (B) a cable nylon thinner than the groove of the screw. In this way, the cable always parts from the same point respect the fixed frame.

Figure 6.3. One of the eight winches of CARCinos in the top and a disassembled winch in the lower part, where it is shown the linear guide

Detailed explanations about the kinematics, performance and specific design applied to the requirements of this prototype can be found in chapter 3. Fig. 6.4A shown the final assembly with the end-effector attached to the rigid frame to perform those experiments that use a constant Jacobian matrix. The detailed design of the second body of the end-effector is described in Fig. 6.4B.

Figure 6.4. A) Passive reconfigurable end-effector from the CARCinos prototype. The main body of the end-effector (a) is attached to the rigid frame while the second body of the end-effector (b) can be moved freely along the vertical rod from the main body. B) Design of the second body of the end-effector. The linear guide (a) is part of the main body. The second body of the end-effector is compound of the main cylinder (b), rotating cylinder (c) and the handle (d). The main cylinder (b) can displace along the linear guide (a) by using an inner linear bearing, the rotating cylinder can rotate around the axis of the main cylinder (b) to align the handle (d). This handle (d) also can move upwards and downwards in order to align the cable attached to it with the center of the rotating cylinder (c) to help solving the Kinetostatics.

6.4.- Winches design

Before the winch design, the cable characteristics are needed to define. The objective of performing secondary tasks requires that the elastic component of the cable is concentrated near the end-effector. By doing this, the compliant actuator can have a shorter secondary cable to move the second body of the platform and its kinematics can be calculated in an easier way. This objective will be one of the most important criteria to select the cable and the winch design.

6.4.1.- Cable selection

The selection of the characteristics of the cable are based on the maximum tension required and also the minimum bending radius. Higher tension requirements will need wider cables while smaller pulleys will require more flexible cable configurations and thinner cables. These relationships are shown in Table 6.4 and Table 6.5. Following the requirements from Table 6.1, a stainless steel 7x19 cable is selected, whose mechanical specifications are detailed in table 6.5, having a Working Load Limit (WLL) of 1.81kN and a Minimum Breaking Load (MBL) of 9.09kN. For security purposes, the force that the motor can exert to the cable has an additional factor of 1.5, being the required force: $800 \cdot 1.5 = 1200N$. The safety factor for each cable is:

$$S.F_{cable} = \frac{9.09}{1.2} = 7.5$$

As it can be observed in table 6.3, the desirable minimum diameter is set as 95mm, with a critical minimum diameter of 73mm.

Table 6.3. Minimum tread diameter for pulleys or sheaves. (From www.tecni-cable.co.uk)

	Desirable minimum [mm]	Desirable minimum [mm]	Desirable minimum [mm]	Critical minimum [mm]	Critical minimum [mm]	Critical minimum [mm]
Cable diameter [mm]	6x7 7x7	6x19 7x19	6x36	6x7 7x7	6x19 7x19	6x36
1.5	67	-	-	44	-	-
2.0	75	76	-	67	43	-
3.0	133	76	-	89	57	-
4.0	167	95	-	111	73	-
5.0	200	114	0	133	86	0
6.0	267	152	76	178	114	63.5
8.0	333	190	95	222	143	80
9.5	400	227	114	267	172	95
11.0	467	267	133	311	200	111
12.0	533	305	152	356	229	127

Table 6.4. Mechanical specifications of the Stainless Steel 7x19 cable, A4-AISI 316, DIN 3060. MBL = Minimum Breaking Load. WLL = Working Load Limit. (From www.tecni-cable.co.uk)

Cable diameter [mm]	Tensile	MBL [kN]	WLL [kN]	Wight per 100m [Kg]
1.5	1570	1.28	0.25	0.86
2.0	1570	2.27	0.45	1.50
3.0	1570	5.12	1.02	3.50
4.0	1570	9.09	1.81	6.10
5.0	1570	14.21	2.84	9.6
6.0	1570	20.46	4.09	13.80
7.0	1570	27.85	5.57	18.70
8.0	1570	33.37	6.67	24.3
10	1570	56.83	11.36	38.10
12	1570	81.84	16.37	54.80

The minimum bending diameter will define the size of the pulleys and the diameter of the drum of the winch, that is where the cable will be coiled. In addition, this diameter will set the relationship between the rotation of the drum and the velocity of the cable deployed with the relation from Eq. 6.3. If a gearbox reduction is also considered with a transmission ratio i , these equations can be reduced if the pitch is neglected as:

$$\dot{l} = \frac{r_D \dot{\theta}_D}{i} \quad (6.4)$$

The relation between the angular torque applied to the drum and the force exerted to the cable, which will be the main source of tension generation, is provided by the following equation:

$$\frac{F_D r_D}{i} = T_D \quad (6.5)$$

6.4.2.- Motor selection

Following the requirements of tension and velocity and Eq. 6.4 and Eq. 6.5, the requirements for the motor can be obtained. According to project specifications, electric servomotors were selected with a range of selection for continuous force until 800N and base speed until 1.5m/s. Imposing the motor speed and torque requirements and knowing that $r_{D_{min}} = 47.5mm$, these expressions, without a gearbox ($i = 1$), are:

$$\begin{aligned} \dot{\theta}_D &\geq \frac{1.5}{r_{D_{min}}} = 42.11 \frac{rad}{s} = 402.07 RPM \\ T_D &\geq 800 r_{D_{min}} = 38 Nm \end{aligned}$$

For security reasons and to allow future expansions of the CDPR, the stall continuous torque is defined as the a 160% of the rated torque, being $T_{D_{stall}} \geq 1280 r_{D_{min}}$. From the wide range of available motors, those with lower power consumption and size are analyzed. Their specific parameters to perform the selection are shown in Table 5. Stall continuous torque has the same value for the same frame size and length, with independence from the rated speed because it is measured at 0 RPM.

Table 6.5. Torque and rated power of motors “Unimotor fm” of 460 Vrms

Frame Size [mm]	75				95				
Frame Length [mm]	238.2	268.2	298.2	328.2	256.9	286.9	316.9	346.9	376.9
Continuous stall torque [Nm]	1.4	2.7	3.7	4.7	2.5	4.5	6.3	7.9	9.3
Rated Power [kW]									
2000RPM	0.27	0.52	0.73	0.93	0.51	0.9	1.23	1.53	1.77
3000RPM	0.41	0.72	1.04	1.31	0.73	1.29	1.76	2.17	2.56
4000RPM	0.50	0.86	1.17	1.59	0.94	1.59	2.2	2.68	3.1
6000RPM	0.68	1.21	1.73	2.14	1.24	2.01	2.64	-	-

The region of valid motors from the catalog, attending to the speed and torque of each motor is shown in Fig. 6.5 Where the frontier curve is defined by an expression based on the power, assuming that the power lost in the gearbox is neglected. The following expression allows to consider just the stall torque and the speed with independence from the drum radius or the gear reduction:

$$T_{D_{stall}} \dot{\theta}_D = \frac{1.5 i}{r_{D_{min}}} \cdot \frac{1280 r_{D_{min}}}{i} = 1920W$$

Due to the consideration of the stall torque instead of the continuous, this power should not be used to compare with the rated power provided by the table 5. Instead, this power value is useful to select the motor before the sizing of the drum and the gear selection. The stall torque value allows to select the motor by using a common torque value for each motor frame size and length.

Figure 6.5. Selection of the motors attending to their continuous stall torque and nominal speed. Black line set the minimum requirement of Torque/Velocity, being the upper part the feasible region. Red dots correspond to the motor with a frame of 75mm while blue dots correspond to 95mm. The size of the dots is proportional to their nominal power. The selected configuration is marked as the 95mm with 3000RPM.

In Fig. 6.5, the motor configurations closer to the minimum requirements are the 75mm and 328.2mm with 4000RPM and the 95mm and 316.9mm with 3000RPM. The ratio expressed in (6.4) and (6.5) of the smaller one is $\frac{r_D}{i} = 0.0036$, while the bigger one has $\frac{r_D}{i} = 0.0052$. The motor chosen is the bigger one because the ratio is closer to $r_{D_{min}}$. Its main characteristics shown in Table 6.6. Bigger motors than those two are not analyzed due to their high volume and power that are not strictly needed for this application. The values of r_D and i are adjusted based on catalogs as:

$$\begin{aligned} r_D &= 76.2mm \\ i &= 16 \end{aligned}$$

Table 6.6. Parameters of the selected motor: 095U3B305BACAA. From: www.emersonIndustrial.com/automation. All data subject to $\pm 10\%$ tolerance

Frame size [mm, mm]	95, 316.9	Winding thermal Time const. [s]	90
Voltage [Vrms]	460	Weight [kg]	7
Stall current [A]	3.9	Shaft diameter [mm]	19
Rated Power [kW]	1.76	Shaft length [mm]	40
Cont. stall torque [Nm]	6.3	Kt [Nm/A]	1.6
Peak torque [Nm]	18.9	R (ph-ph) [Ω]	4.67
Rated torque [Nm]	5.6	L (ph-ph) [mH]	21.09
Inertia [kgm ²]	0.00329	Ke [V/krpm]	98.0

As observed, the rated torque is 5.6Nm, which provide a rated force in the cable of 1175N, 1.46 times higher than the maximum continuous torque needed of 800N. The specifications of the gearbox coupled to the motor shaft is shown in Table 6.7.

Table 6.7. Specifications of the gearbox. From www.servotak.eu

Stages	2
Ratio (i)	16
Nominal torque [Nm]	100
Maximum torque [Nm]	180
Critical torque [Nm]	300
Nominal Speed [RPM]	3000

The servo drive for controlling the motor is the Digitax ST: DST1403B from Emmerson with a nominal current of 4 Amperes (rms) and a peak of 12 Amperes (rms). This drive is able to provide position or set position or torque references to the motor. The encoder read from the motor shaft is an incremental quadrature with 4096 Pulses per Revolution (PPR).

The motors are fixed to the winch structure and provide their power to the drum by a toothed belt (8M-824-50) having a reduction factor of 1:1. The anchor of the motor to the drum allows a linear movement to tighten this belt.

6.4.3.- Drum design

The length of the drum is defined by the amount of cable needed to reach all the regions of the workspace. The distance from any of the last pulleys and the further point of the volume inside the columns of the prototype is the diagonal of the parallelepiped of 9x7.5x6 meters, from the Table 6.1. The needed cable length needs to add the distance from the winch, situated on the floor, to the last pulley, that is 6 meters. The length needed for the cable is:

$$length_{cable}[m] = \sqrt{X_{dim}^2 + Y_{dim}^2 + Z_{dim}^2} + Z_{dim} = 19.16 \rightarrow 25$$

A minimum amount of cable needs to be coiled around the drum, even in those conditions where the needed cable is fully deployed. For this reason, the total amount of cable is selected as 25 meters per winch. The cable coiled around the drum requires a mechanism to align it while coiling and maintain its position without riding on top of itself. This is made with a threaded shaft (Tr 24 x 5) to move a pulley parallel to the drum. The cable turns around this pulley and the coiling is done around the drum with a distance between two turns equal to the pitch of the shaft, 5mm. The turning movement of this threaded shaft is provided by another toothed belt (8M-712-20) between the lower part of the drum and the lower part of the shaft with a reduction factor of 1:1. By using eq. 1, and knowing that there will be always 6 meters of cable without coil, the maximum number of turns of the cable around the drum is:

$$n_r = \frac{25 - 6}{\sqrt{(0.1524 + 0.002)^2 \pi^2 + 5 \cdot 10^{-3}}} \cong 39$$

Each turn, the cable displaces 5mm along the drum so its minimum height has to be $39 \cdot 0.005 = 0.2$ m. Considering the motor and gearbox length, the needed for a heavy winch to compensate the high tensions, security purposes and the adaptability to future applications, the length of the drum is set to 0.45 meters.

The rest of the winch main structure is fixed to the floor plate with M16 screws. Those screws, with the winch mass compensate the tension force of each cable maintaining the structure fixed in its position. The basic CAD components of the winch are described in Fig. 6.6.

Figure 6.6. Design of the main parts of the winch. In (I) and (II), it is observed that the drum (a) coils the cable that comes from the exit pulley (h) and it is aligned with the sensorized pulley (g) that is attached to the moving block (b). This block (b) can displace by using the threaded shaft (c) that turns synchronized with the drum (a) thanks to a toothed belt and gears (d). The drum is actuated by the motor (e) with its gearbox that transmit its power with the toothed belt (f). To resist the upward forces from the cable, the base plate (i) is attached to the fixed structure of the robot with screws. In (III) two winches are situated in their corresponding position over the metal base plate and fixed to it by screws

6.4.4.- Force sensors mechanism

The force sensors, or load cells, for measuring the cable tension can be situated in different parts of the cable: Between the cable and the end-effector a trustful measure can be provided, however the weight of the sensor could alter the cable kinematics and also the data need to be transmitted from the end-effector requiring umbilical cables or fast wireless devices. Another option could be to emplace the sensors in intermediate pulleys, like the last pulleys before the end-effector, however this require a mechanism to align the forces with the load cell. A third option could be to situate the sensor in the winch, after the cable leaves the drum. This position also requires an alignment system and it is not able to measure the efforts exerted by the pulleys after the load cell or the dynamic effects of the cable. However, more compact and modular system, easier to carry and reassemble, can be developed by using this configuration because it isn't necessary to carry additional communication cables to the end-effector or to the last pulley, situated at a high altitude. For these reasons, this last configuration has been chosen.

The load cell is situated in the structure of the winch, as observed in Fig. 6.6 and Fig. 6.7. The main requirements of this assembly are to align the force vector with the axis of the load cell to have a precise reading without losing part of the force with undesired force vector projections in different axes. This alignment is done by attaching the load cell to the pulley in one of its ends and fixed to the moving block observed in Fig. 6.7. With this configuration the angle between the cable entering and leaving the pulley is 90° , so the load cell, situated at 45° respect the moving block should measure directly the cable tension, after the corresponding geometric calculus.

The second requirement of this assembly is to avoid measuring the weight of the pulley with the load cell to don't mix gravity with tension forces. To solve this, a linear guide is situated along the small movement the load cell performs when it is deformed. This lineal guide is located at 45° , as the load cell, so that, it compensates just the gravity force allowing the force component aligned with the load cell.

Figure 6.7. In (I), it is shown the design of the sensorized pulley that obtains the tension of the cable. The cable from the drum of the winch pass through the pulley (a). The load cell (b) measures the force component of the tension, which is aligned with this sensor thanks to the attachment plate (c) that fix it to the moving block (f). The force component of the pulley weight is supported by the bearing (d) that can slide on the surface of 45° defined by the guiding plate (e). In (II), the actual sensorized pulley attached to its corresponding winch.

6.5.- Pillars design

Suspended CDPR require their final pulleys to be in a higher position than the end-effector when they are in static configuration. As observed in Table 1, the inertial frame requires a height of 6 meters. For this reason, the structure has to reach this height and be able to handle the cable forces with the minimum deformation and vibration. The pillars are designed as a modular structure with three pillars of 1 meter tall for each block. The rear column has an inner diameter of 140mm and outer of 170mm while the two front columns has an inner diameter of 100mm and outer of 120mm. 6 blocks of three columns are needed for each pillar, as observed in Fig. 6.8.

Figure 6.8. Design of one pillar. Left Figure (I) shows the current scale of the column (b) respect the winches (a). Both are attached to the ground by screws to the base plate (d). The two pulleys are situated on the top of the columns (c). Figure (II) shows a lower section of one pillar, the base connector (f) is fixed to the base plate (d) by welding. Wider cylinders (g) and thinner cylinders (h) are coupled in the base connector (f) and the intermediate connectors (e). The electric cabinet (j) is fixed by screws to the cabinet support (i), which is fixed by screws to two intermediate connectors (e). Figure (III) is the actual basic structure of one column. Figure (IV) shows a electric cabinet attached to the pillar.

The structure of the pillars is designed based on the maximum tension applied on the top of the pillars. However, in the base of the pillars the maximum torque due to those cable tensions is applied. For this reason, a design of concrete footings is needed to provide the foundations able to maintain the stiffness of the pillars and attach them to the ground, as shown in Fig. 6.9. The pillars are coupled to a metallic base plate of 25mm thickness. This basement provides stability by imposing the loads to the soil by using shallow foundations. A pattern of 10 corrugated bars (8 with diameter of 16mm and 2 with diameter of 20mm in the rear part of the basement and length of 45 and 60 cm respectively) are screwed in the metal plate and bored into the concrete of the foundation. These foundations have an approximate depth of 80 cm. The pattern of the corrugated bars in the metal plate can be seen in Fig. 6.9V, where the two bars of 60cm are situated in the rear part and will be attached to the tensor system of the pillars explained later. The 6 remaining bars of 45cm will be attached to the base plate with screws.

Figure 6.9. Foundations for the pillars of the CDPR. (I, II, III, IV) correspond to the previous holes of each basement. The Steel bars used have 16mm and 20mm diameter. Figure V shows the metal template to align the bars. This metal sheet will be removed and substituted by the base plate with the base connector welded

For security purposes and to provide higher stiffness to the pillars, a tensioned cable mechanism is designed and implemented. This mechanism has two steel cables 7x19 of 10mm of diameter and one of their ends is fixed to the concrete basement inside the rear column by screwing the cables to the corrugated bars of 60cm. Each cable can work with load until 11.36kN. These cables pass through this entire column until the top part, where the cables are coiled around the piece shown in Figure 6.10.e and 6.10.f. This semicircular piece with two flanges to avoid the cables to slip out of the face and transmit a compression effort to the entire column. Those cables are aligned to go down outside the columns until a manual slack adjuster fixed to the metal base plate where the cables can be tensed and provide additional stiffness to the structure. The electrical cabinets are designed to be placed in each pillar. So, a metallic plate is designed to attach them, as seen in Fig. 6.8II and Fig. 6.8IV.

Figure 6.10. Detail of the top of the pillars. In (I), two pulleys (a) are linked to the pillars by screwing the metallic plates (d). The pulleys can rotate around their own axis and also the vertical axis respect the top of the pillar plate (c). To maintain the rigidity of the whole pillar, two cables are attached to the ground and pass around the guide (e) to go inside the rear hole (f) until the floor connection. Figure (II) shows the mechanism implemented in the actual robot

6.6.- End-effector Design

The first experiments require a rigid and heavy end-effector to apply a wide range of forces without altering its position. Attending to these requirements, the end effector has been made of aluminum frames and steel bars. To measure the zero-moment point (ZMP) of the end-effector when it is touching the ground, 4 load cells ELHS-T1 of 5kN with a sensitivity of 20mV/V are situated below its lower vertex. Data from these four sensors are read by the FPGA from a CompaqRIO-9076 situated inside the end-effector to process the ZMP in a soft real-time computing with a deadline of 100ms. The 8 cables are connected to the end-effector through respective universal joints.

Figure 6.11. First version of the end-effector of the CDR. In (I) it is shown the CAD design while in (II) it is the actual end-effector.

A first version of the end-effector is shown in Fig. 6.11. This version helped to perform basic experiments based on movement and stability. The student Yuhua Tang helped in the design and building of this first version of the end-effector as well as analysis of its resistance and deformation. The second version of the end-effector, which can handle higher tension values is shown in Fig. 6.12. This version has the 4 load cells to register the ZMP position and the resultant of the ground reaction magnitude. 4 steel bars, of 30Kg each one, are attached to the rigid frame to increase the total end-effector weight until 152Kg. Their position is selected aiming to preserve the projection of the total center of mass centered in the base area. In addition, those mechanisms to allow the movement of the secondary body of the end-effector are included. In the top part a linear guide is fixed and a moving part is coiled through different rings until the compliant mechanism built in the cable 2, in the lower part of the platform. In the opposite side of the secondary end-effector some springs are attached to compensate the effort exerted by the compliant mechanism and preserve the ability to exert a force to the secondary body in both directions of its DoF. Its movement is measured with a linear encoder Unimeasure LX-EP-40.

Figure 6.12. Second version of the end-effector. The main view seen in (I) shows the load cells (a), the CompactRIO (b), the compliant mechanism (c) and the cable that connect it with the secondary end-effector that has been remarked in yellow. The top view (II) show the linear guide with the secondary body attached to the end of the yellow cable. In (III) the main components of the secondary end-effector: the mobile body (f), the springs to compensate the cable effort (e) and the linear encoder to measure the body displacement (d). A detailed view of the compliant mechanism (c) is observed in (IV) with the rings that guide the cable marked as (g).

6.7.- Electric Design

Each motor requires a servo drive, the model chosen is the Digitax DST 1403B with the 4200-6002 additional harmonic filter. This drive can also provide the values of the speed and current of the motor. This device requires 380V with a nominal triphasic current of 4A and a maximum of 12A so Altech magnetothermal protections of 10A nominal type C are emplaced. Their curve is shown in Fig. 6.13.

Figure 6.13. Trip curve of the selected magnetothermal protection of 10A rated current and type C.

Usually the motors will exert force in a different direction of the load's movement. To convert this braking energy into heat, resistances are required to be connected to the servo drives. These resistances are selected according to the duty expected for the motors. The peak torque of each motor is 6.3Nm while their maximum applied speed is 3000RPM. The peak values of braking energy appear when the maximum torque is applied to a load moving in the opposite direction at its maximum speed. Considering that the load doesn't move faster than its maximum rated due to external forces or inertias, the peak value of the braking power is:

$$P_{BRPeak} = T_{peak}\omega_{max} = 1979.2W$$

Considering the nominal torque of the motors that is 4Nm, the nominal braking power in the worst situation is:

$$P_{BRNom} = T_{nom}\omega_{max} = 1300W$$

Assuming a braking cycle lower than the 100% for breaking with nominal torque and 75% for breaking with peak torque, the selected resistance for each drive is the RE/PR100R-1500W from "Ecomsa".

Each motor has a brake powered by a current of 0.7 A at 24 V able to produce a 12.2Nm torque and an encoder powered by 5V. For this reason, 24VCC and 5VCC power sources are included in each electrical cabinet. Due to the compaqRIO modules cannot provide high power to control the brake and the activation of the servo drives, solid stay relays are used to manage these functions. Those are from "RS" and based on MOSFET with SPNO configuration with a load current of [1, 500]mA and a load voltage of [10, 60]V. The control voltage is [11, 30]V.

The tension of the cables is measured with the load cells from "DPF sensors" with 300Kg and 2mV/V excited with 5V by the amplifiers "Force Iso Flex" that has an output of $\pm 10V$.

For security purposes, security pushbutton switches are emplaced in each cabinet and in the operator desk. All those switches are connected with a common routing around the whole robot to ensure that pushing any of them all the motors will stop. To unify the measures from each cabinet, a common line with 0V is connected to the four electric cabinets.

The compactRIO-9081 has 4 modules for input/output: The NI-9403 allows digital bidirectional input and output at 7 μ s. Useful to read the motor's encoders. The NI-9477 allows outputs from 0 to 60V at 8 μ s requiring the external power source. It is used to enable the drives and deactivate the brakes. The NI-9205 read analogic inputs with 16Bits and 250kS/s like those from the cable's load cells and analogic parameters from the drive like the motor speed and their current. The NI-9264 is an analog output of 16Bit with 25kS/s useful to send the desired value to the drive.

The electric scheme of the robot can be seen in Fig. 6.14. The student Yaru Tang helped in the implementation of the electric cabinet.

Figure 6.14.- Inside of one of the electric cabinets. The drivers (a), the harmonic drives (b), the magnetothermal protections (c), the 5V power source (d), the switch for the secondary power sources (e), the 24V power source (f), the relays (g), the amplifiers of the load cells (h) and the rear part of the emergency button (i).

Figure 6.15. General view of the CDPR with the first version of the end-effector

7.SINGLE BODY UNDERWATER SIMULATION

7.1.- Introduction

When humans are submerged in water, the high pressure, buoyancy forces, viscosity, low temperature, sensory alteration modulate their capability to control the body in that environment (Massion et al., 1995). Without understanding human motor behavior under water, i.e., muscle activity, postural balance, limb kinematics and dynamic effects that water exerts on the body, we cannot appropriately design training modules, underwater tools, or make adaptations to the immediate surroundings of the divers. Research on human motions under water have reported contradictory conclusions that hamper the practical applications of these observations in aquatic explorations. For example, muscle activity during functional tasks were reported to be lower in the water than on the land ((Masumoto & Mercer, 2008)(Bressel et al., 2011)), while the opposite trend was reported in (Kaneda et al., 2012) or (Colado et al., 2008). Cognitive delays were reported in some experiments conducted at 5m depth (Dalecki et al., 2012) while cortical processing delays were not observed in another study (Schneider et al., 2014). Also, the body center of mass displacements have been reported differently in studies involving reduced gravity environments ((Buloup et al., 2016), (Casellato et al., 2012)). It is postulated that characterizing human behaviors on the ground, while controlling for each underwater dynamic variable, can help to clarify these observed controversies and the results can be used to improve aquatics and their underwater applications.

A consistent framework for the human submerged performance is needed for technical diving. This task is risky due to complexity of equipment and technical procedures. Professional divers often carry out underwater tasks such as inspection, cleaning, repair along with manual operations such as welding, cutting, screwing, lifting or dredging (John, 2008). The knowledge of underwater dynamics is also useful to develop algorithms for robots to perform tasks on the seabed (Roque Saltaren et al., 2018). Underwater is also a useful environment to mimic low-gravity in outer space (Neufeld & Charles, 2015). In under water, a body experiences buoyancy force proportional to its volume that counteracts the gravity force proportional to its mass. The relationship between water immersion and space flight was described in (B. Weber et al., 2017), where a similar loss of sensorimotor control is observed in both environments.

In this chapter, the experiments related with the human interaction with the CDPR to simulate underwater conditions were performed in the RoAR Lab at Columbia University by using the Stand Trainer CDPR. In those experiments, the feet are fixed on the ground while the goal is to reach a target farther than the arm's length. In this condition, the body posture and synergies are studied to maintain pointing accuracy and equilibrium. In these experiments, the CoM displacement plays a fundamental role due to its influence on balance, movement synergies and body inertia management ((Berret et al., 2009), (Massion et al., 1995), (B. Weber et al., 2017), (Massion et al., 1993)).

In order to know that the buoyancy forces are applied properly, in the Center of Automation and Robotics, those forces were analyzed with the robot described in chapter 6. With both results: underwater wrench applied to a rigid body by a large scale CRPD and human response to buoyancy simulation, a better understanding of the underwater simulation and its relation with subjects is developed in this chapter.

7.2.- Related work

Aquatic exercises, including walking and running, have been proposed to enhance physical fitness and therapy among humans ((Edlich et al., 1987), (Kaneda et al., 2012)). Forward, backwards and side walking has been used to minimize the drag effects during walking experiments ((Kaneda et al., 2012), (Cuesta-Vargas & Cano-Herrera, 2014)). This research concluded that muscles tend to reduce their activity when submerged in water with the exception of erector spine which increases its activity ((Kaneda et al., 2009), (Colado et al., 2008), (Barela et al., 2006)). However, another walking study reported reduced spinal activity as well (Bressel et al., 2011). Higher activity of muscles was reported in an experiment performed under water when the locomotion speed was fixed (Masumoto & Mercer, 2008). Another study investigated the effect of water depth on walking

((Alkurdi et al., 2017), (Haupenthal et al., 2013)). Studies related with underwater cognitive performance showed significant reduction ((Dalecki et al., 2012), (Schneider et al., 2014)). To avoid the effect of multiple underwater parameters, low gravity experiments are more useful as they isolate the effect of the mass reduction ((Patron et al., 2005), (Casellato et al., 2012)). In some low gravity experiments, the trunk center of mass (CoM) was observed to be displaced beyond the base of support (BoS) while in other similar experiments performed in submerged testbeds, the trunk movement wasn't significantly different from the over ground (Buloup et al., 2016).

Cable-driven Parallel Robots (CDPR), have demonstrated to be a reliable tools to exert forces and moments on the human body and analyze the functional behaviors (Dragoljub Surdilovic et al., 2007)(M. I. Khan et al., 2018). This lightweight active platform can exert equivalent wrenches on the human body to mimic the underwater environment to selectively reflect a specific underwater parameter using appropriate hydrodynamic model (Fossen, 2011).

7.3.- Hypothesis and objectives

There are two main objectives for the experiments of this chapter: the first one is to use the CDPR described in chapter 6 and developed in the Center for Automation and Robotics (CSIC-UPM) to simulate specific forces applied in different points of the end-effector, working as a rigid body. The objective is to perform the desired wrenches with accuracy for a certain fixed position of the end-effector.

The second main objective is to replicate underwater conditions by imposing buoyancy forces on ten healthy subjects by using a cable-driven parallel robot by using the Stand Trainer CDPR from the RoAR Lab in Columbia University. Each subject was asked to perform a specific task under simulated buoyancy forces and normal gravity forces, separately. In this way, it was possible to compare the human performance in both conditions while performing the same tasks. These human behavior and reactions in underwater environment could serve to understand how the human body handle the additional forces that appears when submerged in order to design better algorithms for submarine robots, design better simulations with the CDPR and propose it as a feasible tool for training humans or robots to perform tasks on the seabed with more security, better performance and previous knowledge of their own abilities in that environment.

The main hypothesis of this experiment is that the application of the buoyancy forces on subjects performing reaching tasks on the ground will provide significant differences in the CoM displacement, ground reaction, and lower back muscles activity. Additionally, it is postulated a forward inclined posture of the participants due to the interaction between the gravity forces and buoyancy forces which effectively act at different positions on the body (Massion et al., 1993).

7.4.- Buoyancy Simulation on a rigid body

Buoyancy force was simulated in the CDPR with a rigid-body as end-effector whose characteristics were detailed in chapter 6. This experiment allows to understand the response of heavy loads under high tensions and measure the accuracy of the underwater simulation by tracking the zero-moment point (ZMP) measured by the load cells of the platform. The force distribution when a buoyancy force of 500N is applied at 0.2m from the projection of the center of mass is shown in Fig. 1. This upward constant force is applied with the cables along the blue circle. To verify the accuracy of this applied force the resultant force is measured with the load cells situated in the corners of the base and computed the ZMP that should follow the green circle.

Figure 7.1. Representation of the forces applied to the base of the end effector. Blue circle is the geometric region of the CoB points analyzed. Green circle is the geometric region of the expected ZMP. GC: Geometric Center; CoM: Center of Mass; CoB: Center of Buoyancy; ZMP: Zero-Moment Point; BF: Buoyancy Force; W: Weight; RF: Resultant Force.

The region of the trajectories followed by the ZMP as well as its desired path is shown in Fig. 7.2. It corresponds to a circumference of 0.1m of radius. The point with a maximum radius value is 0.16m while the minimum is 0.08m. Considering the magnitude of the reaction force, the buoyancy force is desired to maintain its magnitude of 500N while moving the application point along the green circle. The end-effector's weight is 152 Kg so 101Kg are expected as reaction force. The maximum reaction force value measured during the buoyancy simulation was 110.9kg, while the minimum was 89.3Kg. The analysis of those errors is made in table 1. The relative error has been obtained considering as a 100% error in the ZMP trajectory when it reaches one of the boundaries situated at 0.33m from the center (making 2 or three load sensors to separate from the ground). The 100% error for the reaction force is when no buoyancy force is applied.

Figure 7.2. In the left side: Trajectory of the ZMP (black points) along the expected trajectory (green circle). Blue circle defines the trajectory of the buoyancy force and the black wide lines represent the stability region defined by the four load sensors. The red dot is the geometric center and the yellow dot is the projection of the center of mass. In the right side: Magnitude of the reaction force from its initial 152Kg to its desired 101Kg along the time.

Table 7.1. Error analysis for a random test

	Desired magnitude	Max. positive error	Max. negative error	Absolute error
ZMP trajectory	0.1m	0.06m (18.1%)	0.02m (6.1%)	0.08m (24.2%)
Reaction Force	101Kg	9.9Kg (9.9%)	12.6Kg (12.6%)	21.6Kg (21.6%)

To obtain the desired wrenches in the platform, a joint space control has been performed following a force reference and a feedback of the tension values read from the winch mechanism described in chapter 6. Figure 7.3 shows both graphs.

In order to check the accuracy and the repeatability, 5 different tests have been performed for this experiment to measure the ground reaction force from each test and the distance of the ZMP from the desired point of the circular trajectory. The results are shown in the table 7.2

Table 7.2. Mean and standard deviation of each test

Ground reaction force [Kg]		ZMP deviation [mm]	
Mean	Std	Mean	Std
102.6	5.0	10.9	8.3
107.0	4.1	10.0	6.7
105.9	3.8	11.3	7.0
105.8	4.2	10.9	7.4
108.6	4.4	11.3	7.3

Table 7.3. Mean and standard deviation of the experiment

	Ground reaction force [Kg]		ZMP deviation [mm]	
	Mean	Std	Mean	Std
Measured	105.1	2.2	10.9	0.53
Expected	101.0	0	0	0
Abs. error	4.1	-	10.9	-
Rel. error	4.06%	-	-	-

Figure 7.3. Desired ground reaction and ZMP deviation as red points and measured data from the test of the experiment showing the mean and the standard deviation as a black cross and line.

7.5.- Buoyancy Simulation on human subjects

The experiments with humans were developed in RoAR Lab in Columbia University. Subjects were right-handed, 6 men and 4 women, and their mass and volumetric parameters are shown in Fig. 7.6. The subjects participated in the experiment on a voluntary basis. The main force applied by the water on a submerged human is buoyancy force. Following Archimedes' principle, the buoyancy force on a submerged body is a function of its volume. This volume of the human body is obtained by calculating the volume of different body segments. As shown in Fig. 1A, the body has 21 segments: one for the head, four for the trunk, four for each arm and four for each leg. Each segment is modeled as an elliptical truncated cone and is defined by five parameters (Fig. 1B) - two principal axes at the base, two at the top and the height. It is possible to obtain the barycenter and the buoyancy force of any group of body segments by measuring from the front and the side. The cable-driven belt is situated in the trunk height corresponding to the trunk center of buoyancy (CoB). This CoB position corresponding to the trunk volume is obtained from the weighed sum of the four trunk segments CoB. Higher volumetric segments have higher CoB values, so the resultant CoB position will be closer to those segments.

7.5.1.- Application of the wrench

The forces are applied on the human body by using a cable-driven parallel robot (Tobias Bruckmann et al., 2015). The CDPR can exert wrenches with a high accuracy over the entire workspace of the human motion (Ghasemi et al., 2009) by precise control of tensions in the cables with on-line measurements of human body position using a motion capture system and wire tensions using force sensors. The system can achieve high accelerations (S. Kawamura et al., 1995) due to low inertia of the cables. The system can be easily reconfigured and wearable due to its soft cable arrangement ((Hong et al., 2018), (M. I. Khan, Santamaria, et al., 2017), (Casellato et al., 2012)). Knowing the position of the barycenter of the selected region of the body and the buoyancy force, a belt with eight actuated cables is placed at the trunk to provide the equivalent force and moment due to the buoyancy forces. The force applied by each cable is measured and the force control loop is closed for each actuator. It was demonstrated that the arm movement in reaching tasks is not affected by the weight support of this limb but the muscle activity changes (Coscia et al., 2014).

7.5.2.-Forces and pose measurement

Buoyancy force ($\vec{B}$) is defined as:

$$\mathbf{B} = \rho_f V g \hat{k} \quad (7.1)$$

where ρ_f is the fluid density, V is the trunk volume, g is the gravity acceleration and $\hat{k}$ is the unit vector that corresponds to the upward vertical direction in the inertial frame. The inertial frame is set with its x-axis oriented to the right of the body and its y-axis towards the front. Ground reaction forces and moments are measured by a force plate in three independent directions during the experiment. The pose of the human subject is measured using a Vicon Motion Capture system at 200Hz. Position of fifteen markers attached to the body are tracked during the experiment (Fig. 7.5A). Using these marker positions, it is possible to track the displacements and orientation of the pelvis, the mid region of the trunk, the upper trunk, the upper arm and the forearm. By using anthropometric tables (Zatsiorsky, 1983), the center of mass of the pelvis, mid-trunk and upper trunk are estimated for the analysis (Fig. 7.4C).

7.5.3- Human Performance Under Simulation

The task in the experiment was to complete one turn on three screws (1, 2, 3 in Fig. 2B) in the order 1-2-3-3-2-1. The screws were located on a table in front of the subject at a distance that required them to bend forward at the trunk to reach. As reported in [57], significant differences in trunk displacement in underwater environment were obtained for far targets. This horizontal distance is set by asking the subject to press their thumb on the 'M₀' screw (Fig. 2A) while standing straight to normalize this distance with subject arm length. Table height is set at 65% of the subject height (Fig. 1D) and the 'M₀' screw was aligned with the center of the subject body. Different alignments have been considered taking the anteroposterior distance and height of the marker proportional to subject height ((Berret et al., 2009), (Casellato et al., 2012)). Each session consisted of 30 seconds of familiarization with the device while not applying any force to the subject. After this, the subject was asked to reach the first screw without bending the knees and complete the task in normal gravity conditions. Once finished, the subject was asked to come back to the straight position and repeat the same procedure in underwater simulated conditions.

Data obtained from the overground condition was compared with the corresponding data from simulated underwater condition. Data from the ten subjects was processed with t-test for a confidence interval of 95%.

Figure 7.4. A) Buoyancy model of the human body, composed of 21 elliptical cone trunks and their barycenter. (B) Elliptical cone trunk of the buoyancy model and the 5 measures needed for each. (C) Center of mass of three segments of the trunk: Pelvis, Mid trunk and upper trunk. (D) The task board situated at a normalized height corresponding to 65% of subject height.

7.6. Results

The body volumetric model of ten different subjects was obtained (Fig. 7.4A). Their human body model was divided into 21 segments. The barycenter of these segments was calculated so they are modelled as elliptical truncated cones (Fig. 7.4B). The model of the trunk was made by four segments and its center of buoyancy was calculated with the buoyancy force applied at that point (Fig. 7.4A). In order to track the movement of the subject while performing the tasks, the center of mass of three trunk segments is calculated (Fig. 7.4C). These segments are the pelvis, the mid trunk and the upper trunk and are independent from the volumetric model. In fig. 7.5, the movement of 15 markers (green dots) is tracked with a frequency of 200Hz to identify 3 reference frames (yellow arrows), one for each CoM as well as the two segments of the arm and the feet.

The volumetric body segmentation (Fig. 7.4A) allows to analyze the subject volume distribution (Fig. 7.6A). Leg volume corresponds to the 8 lower segments and the arms by 4 segments. One can measure the proportional volume of each body segment with respect to the total volume (Fig. 7.6B). The center of buoyancy height varies with the distribution chosen (Fig. 7.6C). The heights of the three CoM are shown for the ten subjects (Fig. 7.6D). Their horizontal location is centered on the pelvis.

Figure 7.5. A) Body kinematic tracked by using 17 markers (green dots): 9 that define the reference frame of upper trunk, mid trunk and pelvis, base of support, 4 that define the base of support and 4 that set the kinematics of the right arm. B) The task is to tighten the screws 1-2-3-2-1, situated in a place that requires the subject to bend forward.

Figure 7.6. Human Volumetric and mass model. A) Human volume of each subject is divided into three different regions: legs (green), lead + arms (Blue) and trunk (red). B) Proportion of each region respect to the total body volume, trunk corresponds to a third of the body volume. C) Height of the center of buoyancy of each subject considering three possible considerations: the entire body (blue), the upper body (green) or the trunk (red). D) Height of the center of mass of each mass trunk segmentation into upper trunk (black), mid trunk (yellow) and pelvis (blue).

7.6.1.- Simulated underwater performance

The measured ground reaction forces during the experiment showed a reduction in the vertical force in the simulated underwater environment when compared to overground (Fig. 7.7A). Significant differences were observed between underwater and ground environment ($p\text{-value} = 3.72 \cdot 10^{-8}$, $t(8) = 20.229$, $p < 0.001$, [95%CI: 14.03, 17.65]). The torque exerted on the ground was also reduced in submerged simulation (Fig. 7.7C) in magnitude and the variance of the distribution ($p\text{-value} = 0.009$, $t(8) = 3.46$, $p < 0.01$, [95%CI: 1.50, 7.49]). The center of pressure of the feet is normalized with respect to the base of support, from the heel to the toe, however no significant differences were found between the results in the two environments ($p = 0.074$, $t(8) = 2.056$, $p > 0.05$, [95%CI: -0.05, 0.85]).

We also measured the activity of the erector spinae muscles of the low back (Fig. 7.7B). We observed that the maximum activity of this muscle was reduced in simulated underwater immersion ($p = 0.022$, $t(7) = 2.93$, $p < 0.05$, [95%CI: 0.36, 3.35]). The Cohen's D for this comparison is 0.87, showing a large effect size.

Figure 7.7. Comparison between underwater and ground environment. Orange bars correspond to ground experiments while blue bars are for simulated underwater tasks. A) Vertical force exerted on the ground without buoyancy (yellow) is significantly different from the underwater simulated environment (blue). B) Activity of the spinae muscle of the low back without buoyancy (yellow) and with buoyancy (blue) are significantly different. C) Ground reaction torque in the X-axis is significantly different with buoyancy (blue) and without buoyancy (yellow). D) Center of pressure of feet is normalized with the mid foot length, however significant differences were not detected between both environments.

Figure 7.8. Center of mass of each segment of the trunk. Their displacements along Y-axis is normalized with the base of support. Upper trunk doesn't show significant differences between the two environments, however, mid trunk and pelvis show significant differences, showing increased forward displacement in underwater simulated environment.

7.6.2.-Trunk displacement

The CoM of the three trunk segments is tracked along the frontal y-axis (Fig. 7.8). The mean distance is considered for each subject and is normalized with the base of support from the center to the toe. We observe a general trend for the CoM to move forward in underwater environment. The Pelvis CoM is maintained in all cases within the BoS in normal gravity and it goes beyond the toe projection in underwater mode. There is no significant difference in the upper trunk displacement ($p=0.316$, $t(8) = -1.078$, $p>0.05$, [95%CI: -41.80, 15.30]), however, the mid trunk section shows significant differences ($p=4.86 \cdot 10^{-4}$, $t(7) = -6.11$, $p<0.001$, [95%CI: -81.25, -35.91]) and also the pelvis ($p=0.040$, $t(7) = -2.522$, $p<0.05$, [95%CI: -45.87, -1.48]). Values of immersed experimentation of subject 10 were lost during the experiment and Pelvis data of subject 6 were not recorded due to recording difficulty of the corresponding marker.

Figure 7.9. Significant differences between trunk segments rotations. Rotations are considered with Euler axis XYZ and they are initialized with the starting position of the subject. There are significant differences in X-axis rotation of mid trunk and upper trunk sections while there are not significant differences in Y and Z axes and neither in X-axis of pelvis rotation. Orange bars correspond to ground experiments while blue bars are related with underwater simulated tasks.

7.6.3.-Trunk rotation

For the same three trunk segments, their rotation was also measured. Upper trunk with respect to the mid trunk, mid trunk with respect to the pelvis and pelvis with respect to the inertial frame. Rotations are measured from the initial pose, that is set when the subject touches the first screw of the task in normal gravity condition. In order to quantify and compare the rotation effect, the XYZ rotation sequence with axes fixed in the body has been chosen. Pelvis rotation doesn't show significant differences in X axis ($p\text{-value} = 0.07$, $t(7) = -2.138$, $p > 0.05$, [95%CI: -13.02, 0.66]), neither in Y-axis ($p\text{-value} = 0.579$, $t(7) = -0.581$, $p > 0.05$, [95%CI: -1.81, 1.10]) or Z-axis ($p\text{-value} = 0.652$, $t(7) = 0.471$, $p > 0.05$, [95%CI: -1.26, 1.88]).

Mid trunk rotation presents significant differences in the X-axis ($p\text{-value} = 0.017$, $t(6) = -3.271$, $p < 0.05$, [95%CI: -16.15, -2.33]). There is no significant difference in Y-axis ($p\text{-value} = 0.216$, $t(7) = -1.361$, $p > 0.05$, [95%CI: -6.73, 1.81]). For Z-axis, there is no significant difference ($p\text{-value} = 0.211$, $t(6) = 1.401$, $p > 0.05$, [95%CI: -1.51, 5.55]).

Upper trunk has significant differences in X-axis ($p\text{-value} = 0.015$, $t(6) = 3.375$, $p < 0.01$, [95%CI: 4.42, 27.73]). There is no significant differences in Y-axis ($p\text{-value} = 0.994$, $t(7) = -0.008$, $p > 0.05$, [95%CI: -3.12, 3.10]) and no difference in Z-axis ($p\text{-value} = 0.955$, $t(7) = -0.058$, $p > 0.05$, [95%CI: -11.16, 10.63]).

7.7.- Discussion

The goal was to replicate the underwater buoyancy force exerted in a single body by using a CDPR, like a mechanical block as in the case of the end-effector and a belt situated at the height of the CoB in the case of the human body. The reactions from the rigid body were analyzed as well as the human behavior and body performance in this condition. One way to verify the similarity of the simulated and the real underwater environment is to perform similar tasks in the two environments.

In human subjects, this simulation considers just the trunk volume of subjects and this corresponds to one third of the total body volume, as seen in Fig. 7.6B. So that, the buoyancy force is exerted to the body part with the higher volumetric value, which is the variable more influenced by the aquatic environment.

Buoyancy force is not applied in upper limbs, head or lower limbs. However, some prior studies have analyzed the influence of low gravity in upper limbs showing differences in muscle activation but not in the muscle synergies or body kinematics. Considering these previous results, we should expect no significant variation in the underwater kinematics of the upper body. A limitation of this simulation is the absence of dynamic water effects like drag forces or added mass. However, a previous study published in (B. Weber et al., 2017) has concluded that variations in the aiming motion while performing tasks that appear in low gravity conditions are not related with water viscosity but the subject cognitive impairment due to the weightlessness. One advantage of a terrestrial simulator of underwater conditions is that it allows to impose any desired set of input forces on the human and record physiological measures with accuracy. For example, muscle EMG have been widely used in underwater experiments of walking and running (Cuesta-Vargas & Cano-Herrera, 2014). Unespected lower EMG values in water than on ground were reported and further analyzed for possible source of measurement errors like inadequate waterproofing, effects of water temperature, the influence of hydrostatic pressure in body stabilization, or underwater stimulation of body mechanoreceptors that could lead to presynaptic inhibition in inter-neuron pathways (Bressel et al., 2011).

The direct result of the application of buoyancy force on the subject is the ground reaction forces. Comparisons of these forces in overground and underwater environment have been performed ((Barela et al., 2006), (Schaefer et al., 2016), (Barreto et al., 2016)). We observed in Fig. 7.7A a significant reduction of the weight due to the upward force and also the reduction in the torque along x-axis (Fig. 7.7C), that correspond to ankles. Despite this lower value, the same dynamics of the body mass is compensated to maintain the body in equilibrium. This means that less ankle torque is needed to maintain the equilibrium of the body, despite the observed forward displacement of the trunk CoM. This is due to the reduction of the perceived weight provided by the buoyancy force. The feet CoP measure does not shown significant differences between both environments, as seen in Fig. 7.7.D, showing that the subjects were able to maintain it in the same region in both conditions by regulating the ankle torque.

Significative change in muscle activity was recorded by using EMG. Because the experiment is performed in dry environment, the mentioned sources of measurement error are not applied. In (Bressel et al., 2011), muscle activity is measured in actual underwater environment, showing a significative reduction and noticing that a 25% or less than the maximum activity is suitable for improving motor control and endurance of trunk muscles. In Fig 7.7B, we observe a significant reduction in erector spinae activity from 25% to 19%. This range is appropriate for this kind of exercises that could be performed in future works.

In addition to fixing the feet on the ground, reaching tasks are proposed (Berret et al., 2009) and applied to underwater conditions ((Buloup et al., 2016), (M. I. Khan et al., 2018)) and low gravity ((Casellato et al., 2012), (Patron et al., 2005)). Antero-posterior position of the CoM of the three trunk segments show significant differences in the pelvis and mid trunk, Fig. 7.8. Upper trunk CoM doesn't show significant difference in forward position. As said, reaching tasks requires to fulfil two objectives: bipedal self-balance and task accuracy. In both cases, normal gravity and underwater simulation, task is completed suscesfully, however, in presence of buoyancy, the body CoM doesn't need to be inside the BoS. It is noticeable how the pelvis CoM of all subjects and the mid trunk CoM of the 75% of the subjects remains inside the BoS in normal gravity while they are displaced forward in underwater. Upper trunk doesn't show significant differences due to the restriction imposed by the task that limits the kinematics of the arm and shoulder, spreading this constraint until the upper trunk.

The task is situated 4.6 cm to the right of the body symmetry axis, this misalignment was set with the intention to detect rotations toward the right. A quantitative measurement of these rotations is performed by comparing the Euler angles of these rotations with the sequence XYZ fixed in the body. Angles are measured from the initial position, that corresponds to the body kinematics when subjects touch the first screw of the task '1' in normogravity. No significant differences have been obtained in Y and Z axis of Euler rotation and neither in X-axis of pelvis. However, significant differences have been obtained in X-rotation for mid trunk and upper trunk. The perception of the tilt has been explained in previous research due to presence of buoyancy which gives a wrong perception of verticality (Massion et al., 1995).

Results obtained in this simulation present patterns similar to those shown in the experiment in low gravity of Casellato et Al. (Casellato et al., 2012): forward movement of the body CoM and reduction of the force and torque to the ground in low gravity conditions. Despite there have been compared the movements in underwater and space flight microgravity, those analysis have been focused on limb velocities and not in muscle synergies and equilibrium.

As conclusion, a simulation of underwater environment has been performed by applying the corresponding buoyancy force in the barycenter of the subject trunk. The results have been compared with those previous experiment of the literature and given the point of view proper of this analysis that doesn't have the undesired underwater perturbations like viscosity, humidity, measurement errors or imprecise buoyancy effect due to volume variations. This way of simulating the underwater environment can be a tool of deeper analysis in more detailed environments or a training device for those environments due to the ability to desired wrenches in the subject.

8.TWO-BODIES UNDERWATER SIMULATION

8.1.- Introduction

Wearable robots (Pons, 2008) are person-oriented robots worn by humans extend the strength beyond the natural ability, restore weak functions or substitute lost limbs. Inside this category, the exoskeletons follow the human kinematic. The analysis of passive trunk exoskeletons from in (Baltrusch et al., 2018) observed some adverse effects on tasks that require large ROM of trunk flexion. To improve the ergonomics of those robots, the compliance is an important aspect that led to the appearance of soft exosuits like (Ding et al., 2017) and elastic actuators as presented in (Cappello et al., 2015) where the stored energy is analyzed.

In this chapter, a background for a trunk wearable robot based on two belts is proposed. The main idea is to control the 6 DoF from one of the belts with 8 cables actuated by external motors while the second belt will be actuated by using the degrees of actuation that are not being currently used by the first belt. This design allows to transmit in a soft way the mechanical tension through cables situated close to the body limb, reducing the risks of external collisions and maintaining the motors outside the body and fixed in an external rigid frame to maintain the capability to exert high wrenches respect to the inertial frame without loading the body with the weight of the motors.

8.2.- Related work

Different trunk kinematic models can be found in literature: in (Preuss & Popovic, 2010), three different models where compared (1, 3 and 7 segments) while Leardini et Al. used a 5 link-segment model in (Leardini et al., 2011) for analyzing elementary exercises. In (Hidalgo et al., 2012) a 6 segments model was able to provide reliable measures for diagnosis and treatment while in (Houck et al., 2006) just 2 sections were needed. The two-belt configuration can impose wrenches in two different segments, however if a model that consider more than two links is considered, the internal forces working along those parts of the trunk could be studied.

Attaching two or more different actuated belts in the trunk could provide some forces applied to different segments. In this way, the total wrench can be spread along different spinal cord regions and also set different perturbations as done by Khan et Al. in (M. Khan et al., 2019). However, if more degrees of actuation are desired, the number of cables that parts from the rigid frame to the body attachment will increase, reducing the Collision Free Force Closure Workspace (CFFCW) defined in (B. Wang et al., 2016).

8.3.- Hypothesis and Objectives

The main objective for this chapter is to increase the quality of the underwater simulation by distributing the wrench exerted by the underwater environment in more than one link of the body. As the proposed simulator aims to be used by humanoids (humans or robots), a user with a trunk with more than one segment is expected. The use of an additional emplacement to exert and distribute the wrenches along the trunk could reduce the harm due to the high pressure that could be exerted when the value of the buoyancy is too high, like when the volume is large. Another advantage of this additional source of wrenches in another point could be the simulation of underwater currents or impacts in the corresponding body segment due to the capacity to control with independence this DoF.

In this way, the main hypothesis of this chapter is that it is possible to control the position and the force of the second belt, modeled as the second end-effector from chapter 4, by using the redundant DoF provided by the motors that act on the main end-effector and without alter the wrench that is being performed in this main body.

8.4. Two-belt mechanism

8.4.1. Design and kinematics

At first, we consider a belt to be adjusted around the waist of the subject. This belt has 6 DoF actuated by using 8 cables attached to the points B_i . Each cable has to be under positive tension (τ_i) that is provided by 8 different motors. Each cable is routed from each motor to their corresponding anchor point in the belt following different belts. Points A_i represent last pulleys positions and are considered fixed points in the inertial frame $\{F\}$. The attaching points are selected according to (Marc Gouttefarde et al., 2015), whose distribution optimize the cable collision-avoidance and the wrench feasibility.

The configuration observed in Fig. 8.1 allows to provide a vertical wrench to the body attending to the friction between the belt and the waist and also two harness attached to the belt help to apply the cable forces in the groins. In this way, this design allows to impose a desired wrench in the hip according to the kinematic expressions observed in (J. P. Merlet, 2008):

$$\mathbf{W}_E = \mathbf{J}^T \boldsymbol{\tau} \quad (8.1)$$

Where $\mathbf{W}_E$ is the wrench applied by the cables to the belt, $\boldsymbol{\tau}$ is the tension value in each cable and $\mathbf{J}$ is the (m x n) Jacobian matrix corresponding to the configuration seen in Fig. 8.1, whose expression is:

$$\mathbf{B}\mathbf{J}^T = \begin{pmatrix} \hat{\mathbf{u}}_i^F & \dots & \hat{\mathbf{u}}_m^F \\ \mathbf{p}_i^F \times \hat{\mathbf{u}}_i^F & \dots & \mathbf{p}_m^F \times \hat{\mathbf{u}}_m^F \end{pmatrix} \quad (8.2)$$

Where $\hat{\mathbf{u}}$ is the unitary vector corresponding to each cable force. The vector from the mobile reference (O_I) and each anchor (B_i) is $\mathbf{p}_i$, which is expressed in $\{F\}$ coordinates.

Figure 8.1. Scheme of the single belt actuated by cables to exert a 6-dimension wrench to the pelvis and the second belt actuated by 2 cables able to exert a torque in the sagittal plane or a downward force to the chest.

8.4.2.- Elastic energy distribution

A redundantly restrained CDPR can provide the same wrench to the end-effector by applying infinite different tension distributions along its cables. In (M Gouttefarde et al., 2015), Gouttefarde et. Al applied the following expression to characterize these possibilities as:

$$BJ^T = \begin{pmatrix} \hat{\mathbf{u}}_i^F & \dots & \hat{\mathbf{u}}_m^F \\ \mathbf{p}_i^F \times \hat{\mathbf{u}}_i^F & \dots & \mathbf{p}_m^F \times \hat{\mathbf{u}}_m^F \end{pmatrix} \quad (8.3)$$

As developed in chapter 4, position and wrench variations can be merged in a single term, obtaining the expression:

$$\boldsymbol{\tau} = \mathbf{B} + \mathbf{A}\boldsymbol{\lambda} \quad (8.4)$$

With $N(\mathbf{J})$ defined as the $(m \times n)$ matrix corresponding to the nullspace of the Jacobian matrix and $\boldsymbol{\lambda}$ as the $(r = m-n)$ vector values over the basis defined by the nullspace.

According to chapter 4 and (Rodriguez-Barroso et al., 2019), a redundantly constrained parallel mechanism with deformable links with k as stiffness value has a total elastic energy defined by:

$$U_T = \frac{1}{2} \left(\boldsymbol{\lambda}^T \left(\sum_{i=1}^m \frac{\mathbf{P}_i}{k_i} \right) \boldsymbol{\lambda} + \left(\sum_{i=1}^m \frac{\mathbf{Q}_i}{k_i} \right) \boldsymbol{\lambda} + \sum_{i=1}^m \frac{R_i}{k_i} \right) \quad (8.5)$$

With:

$$\mathbf{P}_i = \begin{pmatrix} a_{i1}^2 & a_{i1}a_{i2} & \cdots & a_{i1}a_{ir} \\ a_{i1}a_{i2} & a_{i2}^2 & \cdots & a_{i2}a_{ir} \\ \vdots & \vdots & \ddots & \vdots \\ a_{ir}a_{i1} & a_{ir}a_{i2} & \cdots & a_{ir}^2 \end{pmatrix} \quad (8.6)$$

$$\mathbf{Q}_i = 2 \begin{pmatrix} b_i a_{i1} \\ b_i a_{i2} \\ \vdots \\ b_i a_{ir} \end{pmatrix} \quad (8.7)$$

$$R_i = b_i^2 \quad (8.8)$$

This energetic point of view of the elastic cables can provide information related with their tension and deformation. The tension value helps to solve (8.1) for a complete control of the single belt. At the same time, the deformation (δ) can be used to generate a secondary movement that can be used by a second body as proposed in (Rodriguez-Barroso et al., 2018). The elastic energy expressions are:

$$U_i = \frac{k_i \delta_i^2}{2} = \frac{\tau_i^2}{2k_i} \quad (8.9)$$

And with them, tension and deformation boundaries and targets can be imposed for each cable or for the entire mechanism by using their corresponding energy values. Tension limits are based on actuator capabilities or stability, as pointed in (P. Liu et al., 2014) while deformation limits are defined by the springs elastic range. This energy point of view is also useful when the stiffness value is unknown because the relation between the tension applied and the deformation is not clear, like in the case of non-linear elastic materials, unmodeled materials or in the case of the actuation proper of the human or robot when it feels the tension applied. In those cases, the more general expression (8.10) could be used.

$$U_i = \int_0^{\delta_i} \tau_i(\delta_i) d\delta_i \quad (8.10)$$

And applying the expressions developed in chapter 4 for the motor energy:

$$U_{r,a} = U_r + U_{2,1} = U_r + U_{\min} + \int_0^{\delta_{r,2}} \tau_{2,1}(\delta_{r,2}) d\delta_{r,2} \quad (8.11)$$

Where $U_{\min}$ is the energy stored by the springs before their deformation, U_r is the energy applied to the first end-effector and $U_{2,1}$ the energy exerted to the second end-effector, which can be calculated by integrating in each sample of the movement the deformation read by the motor encoder and its tension $\tau_{2,1}$, obtained in an indirect way from the tension measured in the cable ($\tau_{r,a}$) and the tension calculated τ_r .

The feasible nullspace region allows to select a certain range of valid values of U_r while the energy of the motor $U_{i,a}$ can be modified to apply a predefined amount of energy to the upper body or even to measure the response of this limb to the simulation.

8.4.3.- Compliant joining mechanism

The second belt, shown in fig. 8.2, can provide forces in the upper trunk. This second actuated region is useful to increase the surface of wrench application to avoid high pressure regions. This second belt also reduce the forces that the spine needs to exert to maintain the trunk kinematic chain when the forces are applied.

The upper belt is actuated by the frontal force $\tau_{2,1}$ and the dorsal force $\tau_{2,2}$. Both forces act towards the pelvis following the spine and the belly line vertically and are exerted by two different cable tension. Those two forces can exert a rotation in the sagittal plane or/and a resultant downward force applied in the upper trunk.

Forces $\tau_{2,1}$ and $\tau_{2,2}$ are exerted from 2 of the 8 cables attached to the first pelvis belt. Its degree of redundancy is $r = 2$ so this is the base dimension of the first belt Jacobian matrix. Those 2 degrees of actuation allow us to exert 2 additional independent energetic states in the 8 cables. However, it is needed to select 2 of those cables whose energetic value is independent of each other to have the ability to select the tension and deformation of one without affect the other. This cable selection can be done by considering (8.5). This equation

can also provide the energy distribution of each cable according to λ . The geometric shape of this energy distribution respect λ is a parabolic cylinder, which is characterized by one non-null and two null eigenvalues. The cylinder axis direction is defined by the eigenvector (V_{iI}) corresponding to the non-null eigenvalue α_i :

$$P_i V_i = \alpha V_i \quad (8.12)$$

The cables with independent energetic distributions are those whose axis have different directions. This dependence ratio (d.r) can be measured by comparing two cables i and j as:

$$d.r. = |V_i \cdot V_j| \quad (8.13)$$

The selected two cables have certain freedom to impose independent energy values maintaining the desired wrench in the primary belt according to their tension value. However, the deformation value can be used to provide the tension of the upper belt. The transmission of the deformation energy from the lower belt to the tension in the upper belt is performed by the mechanism described in Fig. 8.3, which is attached to the cable r .

In that proposed compliant mechanism, the point D_r is a joint between two different cables: the orange cable exerts its effort to the primary belt, with a spring of stiffness k_r that allow a deformation δ_r . This deformation allows the movement of the point D_r that exert the effort to the blue cable that pass around two pulleys $C_{r,A}$ and $C_{r,B}$ and pull the upper belt with a force $\tau_{2,1}$.

The elasticity of the blue cable is imposed with the spring with stiffness value $k_{r,2}$. Considering the resultant stiffness seen from A_r , and known the value of $k_{r,2}$, the energy stored by the r actuator is:

$$U_{r,a} = \frac{\tau_{r,a}^2}{2(k_r + k_{r,2})} \quad (8.14)$$

Due the parallel configuration of both springs, they share the same deformation:

$$\delta_r = \delta_{r,2} = \sqrt{\frac{2U_{r,a}}{k_r + k_{r,2}}} \quad (8.15)$$

Figure 8.2. Scheme of the compliant mechanism attached to the cable r able to transmit its tension to the first and second belt.

And the tension exerted by each cable end is:

$$\tau_r = k_r \delta_r = \frac{k_r}{k_r + k_{r,2}} \tau_{r,a} \quad (8.16)$$

$$\tau_{2,1} = k_{r,2} \delta_r = \frac{k_{r,2}}{k_r + k_{r,2}} \tau_{r,a} \quad (8.17)$$

In the case of an unknown value of $k_{r,2}$, from (8.11) is obtained the value of $U_{r,a}$. The value of U_r is:

$$U_{r,a} = \frac{k_r \delta_r^2}{2} + U_{r,2} \quad (8.18)$$

Where the energy applied to the upper belt ($U_{r,2}$) in its front part could be imposed to fulfill a desired performance in the subject, used as a measured variable, used from a previous model of the trunk response or obtained by using (8.10) with the following expressions (8.19)-(8.21). The elongation $\delta_{r,a}$ is obtained by the encoder of the actuator and the following relation is defined due to the parallel configuration of the mechanism:

$$\delta_{r,a} = \delta_r = \delta_{r,2} \quad (8.19)$$

The tension exerted by each branch of the compliant mechanism can be obtained with the Hooke's Law and the composition of tensions in a parallel configuration of springs:

$$\tau_r = \delta_r k_r \quad (8.20)$$

$$\tau_{r,2} = \tau_{r,a} - \tau_r \quad (8.21)$$

Being the value of $\tau_{r,a}$ directly measured by the load cell of the actuated cable from the compliant mechanism.

The blue cable is coiled around two pulleys that will transmit the cable tension to the pelvis belt ($\mathbf{F}_{r,A}$ and $\mathbf{F}_{r,B}$). These two pulleys are fixed with a rigid structure to preserve the distance between them and their position respect the pelvis belt. Considering this structure, the resultant forces seen by the pulleys are:

$$\mathbf{F}_{r,A} = \tau_{2,1} \hat{\mathbf{k}}^M \quad (8.22)$$

$$\mathbf{F}_{r,B} = \tau_{2,1} \quad (8.23)$$

Considering that massless pulleys the input and output tensions are equal: $\tau_{2,1} = \tau_r$. The structure matrix of the pelvis belt ($\mathbf{J}_I^T$) can be upgraded adding the wrenches due to the compliant joining mechanism:

$$\mathbf{W}_{E_I} = \mathbf{J}_I^T \boldsymbol{\tau}^I = \left(\boldsymbol{\Lambda} \mathbf{J} + \frac{k_{r,2}}{k_r + k_{r,2}} \mathbf{J}_{cjm} \right)^T \boldsymbol{\tau}^I \quad (8.24)$$

$$\mathbf{J}_{cjm}^T = \begin{pmatrix} \dots & \mathbf{R}_{M_I}^0 \hat{\mathbf{k}}^M + \hat{\mathbf{u}}_r & \dots \\ \dots & \mathbf{p}_{r,A}^F \times (\mathbf{R}_{M_I}^0 \hat{\mathbf{k}}^M) + \mathbf{p}_{r,B}^F \times (\hat{\mathbf{u}}_r) & \dots \end{pmatrix} \quad (8.25)$$

$$\boldsymbol{\Lambda} = \begin{bmatrix} \ddots & 0 & 0 \\ 0 & \frac{k_r}{k_r + k_{r,2}} & 0 \\ 0 & 0 & \ddots \end{bmatrix} \quad (8.26)$$

With $\mathbf{p}_{r,A}^F$ the vector from O' to $C_{2,A}$ and $\mathbf{p}_{r,B}^F$ the vector from O' to $C_{2,B}$. The term $\mathbf{J}_{cjm}^T$ has non-null terms just in those columns corresponding to cables with a compliant joint mechanism. The previous Jacobian matrix ($\mathbf{J}_I$) is also multiplied by a diagonal matrix with non-null terms corresponding to those selected redundant cables. Considering these changes, the upgraded tension distribution ($\boldsymbol{\tau}^I$) needs to be modified in order to exert the same wrench to the pelvis belt.

Wrench exerted to the chest belt ($\mathbf{W}_{EII}$) is provided by the tension from the selected redundant cables. According to (8.15), the structure matrix of the upper belt ($\mathbf{J}_{II}^T$) defined in Fig. 8.2 is:

$$\mathbf{W}_{EII} = \mathbf{J}_{II}^T \boldsymbol{\tau}^I \quad (8.27)$$

$$\mathbf{J}_{II}^T = \frac{k_{r,2}}{k_r + k_{r,2}} \begin{pmatrix} \dots & -\mathbf{R}_{M_{II}}^O \hat{\mathbf{k}}^M & \dots \\ \dots & \mathbf{p}_{r,C}^F \times (-\mathbf{R}_{M_{II}}^O \hat{\mathbf{k}}^M) & \dots \end{pmatrix} \quad (8.28)$$

Where $\mathbf{p}_{r,C}^F$ is the vector from $\mathbf{O}_{II}$, fixed in the moving frame $\{\mathbf{M}_{II}\}$.

8.5.- Theoretical results

An external rigid parallelepiped frame with dimensions [3, 2, 2] meters is defined. The eight pulleys part from the superior corners and attached to a pelvis belt with the configuration shown in fig. 8.1. The anchors from this belt (B_i) are placed in the corners of a virtual parallelepiped with dimensions [0.2, 0.3, 0.04] meters. The moving frame attached the pelvis belt is centered in $\mathbf{O}^F = [1.5, 1, 1]$ meters.

The first step is to choose the spring stiffness. Usually high stiff cables are chosen to neglect their elastic behavior when they work with springs. High stiff actuators provide fast system response but they could restrict the human movement and could require fast control algorithms to maintain the tension values within the boundaries.

In Fig. 8.3, the total elastic energy stored in the springs shows that it depends on the tension configuration given by the nullspace and the spring stiffness. The energy shape respect the nullspace independent variables (λ_1 and λ_2) defined in (3) corresponds to an elliptic paraboloid centered in [0, 0], as demonstrated in (Rodriguez-Barroso et al., 2019). The objective is to have a wide energy range along the feasible tension distribution region (Ω). Better ranges are obtained for lower stiff actuators, wider tension available ranges and higher wrenches in the end-effector, so in this case it is taken $k_i = 500 \frac{N}{m}$ and a pelvis wrench of $\mathbf{W}_E = [0, 0, 313.6 | 0, -5, 0] \left[N \left| \frac{N}{m} \right. \right]$, which corresponds to an upward force of 40% of 80Kg assuming a percentage of a common bodyweight and a backward pelvis torque of 5 N/m. With these conditions, the minimum value for the total elastic energy is $U_{min} = 53.55J$ and the maximum: $U_{max} = 90.55J$. The tension limits are selecting according to the spring elastic region as: $\tau \in [5, 500]N$.

Figure 8.3. Total elastic energy stored in the 8 springs ($\sum_i^8 k_i$) of the pelvis belt described in Fig. 8.1 in function of the nullspace and individual spring values inside the feasible region (Ω)

The next step is to find two cables whose energy can be set independently. The shape of the energy values in function of the nullspace is a paraboloid cylinder and their corresponding axes for each cable are obtained from

the eigenvectors from (5): $V_{1,I} = V_{3,I} = V_{5,I} = V_{7,I} = [-0.3399 \quad -0.9405]^T$ and $V_{2,I} = V_{4,I} = V_{6,I} = V_{8,I} = [-0.9405 \quad 0.3399]^T$. It is observed that applying (8.13) both cable groups are linearly independent so one cable from each group can be chosen to implement the compliant joining mechanism to exert the chest belt wrench. In this case, cables 3 and 6 are selected to provide this redundant actuation. Their corresponding elastic energy and their region of feasible tension distribution is observed in Fig. 8.4.

Figure 8.4. Upper figures show the elastic energy stored in cables 3 and 6 respect the nullspace variables. Lower figures correspond to the region of feasible tension of cables 3 and 6 (in green). Black line corresponds to the minimum allowed energy and the red one to the maximum

Once the redundant cables are selected, the Jacobian matrix (J) needs to be upgraded to include the effects of the cable routing in the compliant mechanism according to (8.24). With this new Jacobian matrix (J^I) the tension distribution needs to be recalculated (τ^I).

The stiffness of the compliant mechanisms have to preserve the previously selected values $(k_3 + k_{3,r}) = (k_6 + k_{6,r}) = 500 \frac{N}{m}$ so according to (8.20) and (8.21), springs $k_{r,2}$ are selected according to the ratio of effort desired in the chest belt respect the redundant cables from the pelvis belt. Different spring couples are chosen, and shown in table 8.1, to compare the mechanism behavior.

Table 8.1. Compliant joining mechanism springs

Configuration	Springs stiffness values			
	$k_3 \left[\frac{N}{m} \right]$	$k_{3,2} \left[\frac{N}{m} \right]$	$k_6 \left[\frac{N}{m} \right]$	$k_{6,2} \left[\frac{N}{m} \right]$
A	250	250	250	250
B	250	250	150	350
C	150	350	250	250
D	150	350	150	350

The spring selection is an important task because the stiffness proportion between them will affect the forces imposed by the compliant mechanism. In this way, higher values of $k_{r,2}$ than k_r will modify J^I in a higher way and will exert higher forces in the chest belt. The energetic boundaries set to the motors that act the cables impose restrictions to the mechanism deformation so regarding the spring stiffness the region of feasible tensions (Ω) has different shapes as observed in Fig. 8.5. This result shows that Ω usually shrinks due to the higher perturbation forces that appears in the pelvis belt when $k_{r,2}$ increases. This make the rest of the cables to act against these perturbations to maintain the pelvis wrench, working closer to the actuator energetic boundaries. However, in those cases the stiffness asymmetry allows to handle a wider elastic energy that implies a higher range of forces applied to the chest belt.

Figure 8.5. Region of feasible tension distribution (Ω) for different springs shown in Table I. The total elastic energy (U_T) stored in all springs is represented as well as the energetic boundaries of redundant cables.

Maximum and minimum Total energy values from the Fig. 8.6 are shown in table II:

Table 8.2. Total elastic energetic ranges

Max. / Min. total elastic energy				
Config.		$U_T[J]$	$U_3[J]$	$U_6[J]$
A	Max.	90.55	13.07	9.27
	Min.	53.55	0.49	0.06
B	Max.	83.44	13.08	7.27
	Min.	29.64	0.43	0.03
C	Max.	81.10	10.15	8.99
	Min.	29.00	0.37	0.05
D	Max.	81.09	10.06	11.34
	Min.	26.59	0.36	0.04

The minimum total potential energy is obtained for $\lambda = [0,0]'$ in all the cases. The maximum is obtained in $[170,90]$ for case A, $[-230, 30]$ for case B, $[-200, 110]$ for case C and $[-230, 40]$ for case D.

Table 8.3. Energetic parabolic cylinder directions

Configuration	$V_{3,I}$	$V_{6,I}$	$d.r$
A	[0.584, -0.812]	[-0.841, -0.541]	0.052
B	[0.272, -0.962]	[-0.976, -0.219]	0.054
C	[0.644, -0.765]	[-0.789, -0.614]	0.039
D	[0.687, -0.726]	[-0.753, -0.658]	0.041

Table 8.3 shows the variations of the parabolic cylinder's direction corresponding to the elastic energy stored in cables 3 and 6. A low dependence ratio is obtained for the 4 spring configurations showing that the compliant joining mechanism doesn't exert influence enough to invalidate the redundant cable selection.

Figure 8.6. Elastic energetic ranges of redundant cables for the four spring configurations (A, B, C, D), (Green bars). Force ranges applied to the chest belt by the redundant cables (Red bars)

With the region Ω shown in Fig. 6 provided by the intersection of the 8 regions Ω_i corresponding to each cable, it is possible to obtain the energy ranges of the redundant cables (3 and 6) seen in Fig. 7. In this figure, the maximum and minimum forces exerted to the chest belt by the compliant joining mechanism are shown. It is noticeable that the maximum cable 3 force ranges are obtained for the cases C and D while maximum forces for the cable 6 are provided by the configuration B and D. As expected, those configurations correspond to those with a bigger $k_{r,2}$ stiffness value than k_r .

Finally, the wrench applied to the chest belt is calculated by using the compliant joining cables range of tension. These tensions ($\tau_{2,1}$ and $\tau_{2,2}$) are multiplied by the Jacobian matrix corresponding to the chest belt to obtain its controllable range of forces (T_{YII} and F_{ZII}). Fig. 8 shows the feasible regions attending to the four steps given from the nullspace feasible tension distribution, the energetic values of the redundant cables, the possible tensions of the compliant joining mechanism and the wrench set of the chest belt.

Figure 8.7. Feasible working regions from the tension distribution to the final wrench in chest belt. 1) Region of feasible tension distributions expressed in the nullspace basis. 2) Region of valid redundant cable energy. 3) Region of feasible forces exerted by the compliant joining mechanisms. 4) Region of the possible wrench applied to the chest belt.

8.6.- Experimental development

8.6.1.- Set-up of the experiment

The experiment has been performed with the prototype described in chapter 6 where the position of the pulleys and the end effector is shown in table 8.4. The objective is to apply an upward force of 500N at 200mm from the geometric center, in the X axis, simulating a buoyancy force. The expected reaction force in the end-effector of 152Kg is a force of 101Kg at 100mm at the left side, in the X axis. Maintaining this effort, the second body of the end-effector is controlled by using the compliant mechanism described in chapter 3 with the method described in chapter 4.

Table 8.4. CDPR parameters

Element	Pulleys 1A/1B	Pulley 2A/2B	Pulley 3A/3B	Pulley 4A/4B	End effector CoG/Size
Position [mm]	[-123.9, 92.5, 6000]	[9780.1, -92.5, 6000]	[10091, 5952.5, 6000]	[123.9, 6244.4, 6000]	[4814, 4214, 440]
	[123.9, -92.5, 6000]	[10027.9, 92.5, 6000]	[9844.1, 6137.4, 6000]	[-123.9, 6059.5, 6000]	[628, 768, 648]

The characteristics of the springs used for the experiment are shown in table V. These springs were used to build the compliant mechanism to exert the effort of one cable to the two bodies of the end-effector.

Table 8.5. Spring parameters

Material	Steel
Free length	44.1mm
Maximum length	73.80mm
Outside diameter	6.3mm
Wire diameter	0.9mm
Initial tension	37.1N
Stiffness	1.06N/mm

The values of the elastic range of tension and feasible elongation before going into the plastic state are shown in table 8.6 for different configuration of those springs. Being the elongation the difference between the free and the maximum length. The selected configuration for this experiment is based on 2 springs in series for the main body and other two springs in series for the second body. Series configuration provides a larger elongation capability by reducing the equivalent stiffness constant, increasing the energy storage capability of the configuration and allowing wider movement of the second body of the end-effector. On the other side, the parallel configuration allows to increase the range of working tension.

Table 8.6. Spring configuration parameters

Spring composition	Elongation [mm]	Tension [N]	Equivalent Stiffness [N/m]
59.4	[37.1, 68.58]	0.530
89.1	[37.1, 68.58]	0.353
29.7	[74.2, 137.16]	2.12
59.4	[74.2, 137.16]	1.06
89.1	[74.2, 137.16]	0.707

The objective of this experiment is to simulate the buoyancy of the body while a variable, independent and controlled effort is imposed to the second body of the end-effector that would conform the upper belt, which has 1 DoF in this case. The desired imposed wrench to the main body of end effector is $W = [0, 0, -500, -500 \cdot 200, 0, 0]$ [N, N·mm]. Exerting this wrench, the redundant configuration of the CDPR provides the feasible nullspace for each cable seen in Fig. 8.8 and for the entire CDPR seen in Fig. 8.9. The method used is based the chapter 4.

Stiffness value of the nylon cable and friction with the coiling elements have been neglected.

As observed in Fig. 8.9, the CDPR feasible nullspace region always will be a subset of the corresponding to a rigid links parallel mechanism. Fig. 8.8 allow to select those cables that allow a wider range of tension to be able to set in them the compliant mechanism that exert the effort to the second body of the end-effector. The cable tension for each one of the corners marked in Fig. 8.9 is shown in table VII.

Figure 8.8. Feasible nullspace region corresponding to each cable. Red line corresponds to the maximum allowed energy while the black line is the minimum.

Figure 8.9. Feasible nullspace region corresponding to the end-effector. Grey region corresponds to a parallel mechanism able to push the load while the red one corresponds to the CDPR. A trajectory A-B is marked.

Table 8.7. Tension distribution in the boundaries of the feasible nullspace region

Nullspace position	τ_1 [N]	τ_2 [N]	τ_3 [N]	τ_4 [N]	τ_5 [N]	τ_6 [N]	τ_7 [N]	τ_8 [N]
[-81.12, -21.7]	159.6	5.7	4.6	50.1	87.4	202.3	87.9	119.1
[91.68, -15.84]	69.7	4.7	97.2	51.1	5.2	201.3	168.5	119.2
[-77.49, -107.1]	158.6	49.7	5.1	4.6	86.4	244.0	88.6	79.7
[94.14, -101.5]	69.4	48.8	97.0	5.5	4.8	243.2	168.7	79.8

As seen in table 8.6, the maximum tension allowed in a combination of 2 springs in series is 68.58N so, in order to perform an experiment where any region of the feasible nullspace region can be selected, the chosen cables must provide a range of tension between those values. Those cables are the 2 and the 4, as shadowed in table 8.7 and the compliant mechanism has been installed in cable 2. Attending to the nullspace direction corresponding to the cable 2 from Fig. 8.8, a trajectory perpendicular to that direction is defined in Fig. 8.9 to increase the energy range of the cable 2 aiming to perform wider translations with the second body of the end-effector.

The objective of this experiment was to move the second body of the end-effector attending to the available feasible nullspace region, following the trajectory from A to B observed in figure 8.9. The expected tension values go from 5.2N in A: [5.28, -18.77] to 49.3N in B: [8.33, -104.3].

Figure 8.10. Scheme of the proposed experiment for multi-body end-effector. The buoyancy force (BF) is applied at a distance L_{CoB} of the geometric center of the base (GC). The value of the zero-moment point (ZMP) is normalized respect the position of the measured center of mass (CoM). The displacement of the second body ($\delta_{2,2}$) is registered from the position where the spring has no elongation.

Figure 8.11. Compliant mechanism for acting on the two bodies of the end-effector. At left, a scheme of the spring's configuration and the cable routing, taking in account the reaction forces $F_{2,X}$ that requires additional Jacobian matrices. At right, the mechanism signaled in the actual end-effector, where the second body is in the upper part and its movement registered by a linear encoder as $\delta_{2,2}$.

8.6.1.- Experimental results

Ten tests have been performed for this experiment in two different days and waiting at least 20 minutes between experiments to guarantee their independence. The measures taken by the ground load cells are the ground reaction force and the ZMP, as described in chapter 7. With the linear encoder, the displacement of the second body of the end-effector is measured respect the position of the first body. The mean and standard deviation for the ground reaction force and the ZMP position for each test is shown in table VIII as well as the maximum displacement of the second body of the end-effector. The mean and standard deviation of the entire experiment considering all the tests is shown in table 8.9.

Table 8.8. mean and standard deviation of each test.

Ground reaction force [Kg]		ZMP X [mm]		ZMP Y [mm]		Second body max. elongation [mm]
Mean	Std	Mean	Std	Mean	Std	Mean
93.9	1.7	-437.0	12.0	364.2	5.8	12.3
98.4	1.6	-431.1	12.1	372.0	5.7	16.7
99.0	1.6	-434.9	12.3	373.3	5.4	21.1
98.4	1.8	-422.6	11.2	366.4	5.3	10.8
98.6	1.7	-431.1	11.3	368.8	5.5	32.3
95.2	1.9	-428.6	14.1	364.7	6.5	6.7
95.1	1.7	-429.0	14.3	364.7	6.5	14.0
88.7	2.0	-439.7	17.2	367.9	8.7	15.6
91.5	1.6	-447.7	15.7	365.8	7.3	14.2
92.3	1.7	-456.7	14.7	367.3	8.4	17.3

Table 8.9. mean and standard of the experiment.

	Ground reaction force [Kg]		ZMP X [mm]		ZMP Y [mm]		Second body max. elongation [mm]	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Measured	95.1	3.5	-435.9	10.1	367.5	3.1	16.1	6.9
Expected	101.0	0	-430	0	330	0	20	0
Abs. error	5.9	-	5.9	-	37.5	-	3.9	-
Rel. error	5.8 %	-	1.4 %	-	11.4 %	-	19.5 %	-

The mean and standard error of the experiment were obtained from the mean values of each one of the ten independent test performed. The value of the relative error of the ZMP X and ZMP Y have been obtained considering the measure from the right and lower boundaries of the stability region, respectively, defined by the load cells. This stability region is a square of 660mm side.

Figure 8.12. Representation of the errors (black bars) and the desired values (red dots). Black cross is the mean value of the 10 measures while the bars represent the standard deviation from that mean. The representation of the ZMP is inside the stability region (wide black line) with the dotted line marking the mid-section of this square.

8.7.- Discussion

The method proposed in this chapter for controlling two bodies of the end-effector is based on the mechanism proposed in chapter 3 with the analysis and results from chapter 4. The experiments were performed in the CDPR whose design is detailed in chapter 6.

The redundant configuration of a cable-driven robot has been used not only to impose a wrench to the main body but also the additional cables are used to exert a wrench to another limb. In the proposed case, the 6 DoF from the Pelvis can be controlled aiming to relief part of bodyweight while 2 DoF of the upper trunk are controlled to help in the body stabilization and to spread the external wrench over different body limbs.

The theoretic approach presented in this chapter allows to relate the behavior of the compliant mechanism from an energetic point of view. As observed, lower stiffness of the elastic components stores more energy for the same tension value. However, those elastic components must allow high deformations to reach the required tension. This energy can be transmitted to other bodies of the end-effector to perform movement or wrenches respect to the main body or other bodies. The tension control is performed in closed-loop and, as said in (Robinson, 2000): “closed-loop force bandwidth for series elastic actuators are independent of the spring stiffness that senses the force”. This is because with lower stiffness joints the controller gain can be increased to compensate the displacement needed to perform in order to reach the same tension value as a stiff joint.

The selection of the stiffness in each part of the compliant mechanism is useful to choose if the stored elastic energy will be converted more into deformation or tension. As observed in Fig. 8.6, the selection of different stiffness values, as shown in table 8.1, allow to exert more or less tension to the second body: higher

stiffness in the spring attached to the main body reduces the capability to act on the second body while higher stiffness in the spring attached to the second body increase the wrench to that body.

In Fig. 8.7, a graphic calculation of the feasible torque and vertical force that can be exerted to the secondary body is shown, which is the belt attached to the chest. As observed in the green polygon of that picture, a wide range torque can be exerted to help the upper trunk to follow the requirements of the underwater simulation, in addition, a vertical force that aims to join the chest and the hip belt can be regulated. This vertical force could also help to maintain the position of the upper belt translating this effort to the shoulders, as observed in Fig. 8.1.

The experiment with the prototype aims to demonstrate the validity of the control of 6 DoF of the main end-effector of 152Kg and simultaneously the control of the second body that has 1 DoF respect the main body. This second body, situated on the top of the main body simulates the belt situated in the chest while the main end-effector simulates the hip belt. As observed in the results, the main end-effector has a very good precision and repeatability, attending to the reduced standard deviation in independent experiments, however noticeable errors are detected in the accuracy of the vertical force (5.9Kg) and the Y-axis of the ZMP (37.5mm). The source of the vertical force error could be related with the distance from the tension load cells situated in the winches, far from the end-effector, that are unable to detect the disturbances produced by the upper pulleys and the hanging cable weight. The error in the ZMP, could also be due to the same measurement imprecision because the end-effector is not centered in the workspace, making that some of the tensions have more influence on the wrenches exerted to the end-effector due to the different cable's inclination and their different force vector applied to each attachment point of the end-effector.

In order to fulfill the requirements of the engineering methodology, a correction for these errors can be applied to the control algorithm based on the result of these experiments. This correction will be based on a decrease of the vertical force demanding and a correction torque imposed in the task space to move the ZMP to the desired point. However, attending to the scientific methodology, the source of this errors is needed to analyze by making new hypotheses about the source of this errors, performing more accurate dynamic models of the cable and pulleys to include them in the control and comparing the results. Also, better calibration of the ground and cable load cells and improving the control algorithms for higher dynamic responses.

The exertion of wrenches in two different bodies of the end-effector allow to spread the wrenches of the simulation along different parts of the body, like the hip and the trunk. This can help to increase the quality of the simulation because it can be exerted to humanoids with at least 2 limbs in their trunk. In tests with humans, this tension spread could help to apply higher forces without producing harms due to the high pressure in one specific region of the body. In humanoid robots, this augmented simulation could help to improve the algorithms in more complex robots. The second body could also be used to simulate underwater currents that could affect the stability of the body or also simulate collisions with the environment.

9. CONCLUSIONS

Several conclusions can be obtained from the discussions performed in each chapter. In this chapter, a review of those results and interpretations is performed in accordance with the proposed final objectives defined in chapter 1. In that chapter, the state of the art of the CDPR technology was studied to know if they could be a feasible tool to simulate the underwater environment attending to the requirements that some underwater robots developed in the Center for Automation and Robotics (CSIC -UPM) could need. The redundancy of actuators seemed to be an interesting field of research to increase the quality of the simulations attending to the multi-limb structure of the robots because having more actuators than degrees of freedom could allow to have additional DoF in the end-effector in order to control additional parts of the end-effector, that is the underwater robot.

In chapter 2, the redundancy resolution was analyzed and the first result was the analysis of the maximum wrench and cable tension that appears in suspended CDPR when there is not maximum cable tension limit. It has been also defined the best regions of the workspace to perform specific wrenches depending on the direction of the desired wrench. This is useful to size actuators and define specific working regions in the workspace where a wide range of wrenches are desired in the end-effector.

The second main conclusion of that chapter was the analysis of optimal tension distribution when high wrenches are exerting and the procedure to reach them quickly. The proposed method allows to reduce the time required to achieve those wrenches that are far from the initial wrench. This method is useful when high efforts are exerted in a fast way like in those tasks that require fast and strong wrenches like in pressing or drilling. In the proposed simulator, this fast tension planner resolution could help to move between different configurations that can impose wrenches or displacements in the additional body limbs. In addition, some impacts could be simulated in the underwater robot by exerting the analyzed maximum wrenches in a fast time.

Once the method for handling the redundant configuration was developed in chapter 2, it was used in a novel application in chapter 3. A novel CDPR with a reconfigurable end-effector by using a “compliant actuator” setup was built, “CARCINOS CDPR”. This mechanism was able to control the main body of the end-effector and the secondary, which has 1 DoF respect to the first one. The proposed design was initially simulated within MSC ADAMS with a range of movement of the end-effector mechanism of 170 mm with an 0.63% of error with respect to the theoretical results.

The experimental tests validated the simulated model with a 5.4% error, which can be seen as suitable for the intended application due to the intended human–robot collaboration and the high elastic effects present in the robot. This compliant actuator mechanism is open to a wide range of applications related to end effectors with many DoF where they are controlled by using the redundancy of the external actuators.

Attending to relationship between the forces and displacements in the elastic mechanisms, the potential energy is considered for the analysis in chapter 4 and an equation was developed to obtain its value respect the tension distribution. Knowing the range of feasible elastic energy in one part of the mechanism it could be possible to select the appropriate stiffness value and handle unexpected motions of the underwater robot. One secondary application was developed with this energetic conception and methodology based on the control of a passive gripper.

In order to perform simulations of high-quality, a dimensional synthesis is performed to size the CDPR based on the Parameter Approach method using 5 parameters and 4 indices to size the structure and end-effector as well as the stiffness of the springs attached to the cables. The high-quality simulation was defined in terms of the size of the feasible nullspace to perform wider ranges of movements or wrenches in the secondary body of the end-effector, setting the tension values far from their boundaries and increasing the value of a condition index with physical meaning. A visual analysis has been applied in first place to have enough information to set restriction values and volume of analysis inside the workspace of the robot in order to have a single scalar value of each index.

It is observed that a CDPR should be taller enough to provide low secure tensions, but lower enough to provide an appropriate stiffness and redundant capacity. Higher stiffness is obtained with squared bases while wider available nullspace regions are obtained also with rectangular bases.

Those results have been used to design and build a CDPR able to provide the imposed restrictions. Some additional constraints have been added due to economic and logistic aspects like the price of building higher structures and the available space.

In chapter 6, the buoyancy effects are simulated using a cable-driven robotic platform that exerts equivalent buoyancy forces on the user. The detailed prototype was used to verify the precision and accuracy of

the applied buoyancy while the Stand Trainer from the RoAR Lab was used to characterize the human performance in a simulated underwater environment.

Several studies have analyzed muscular activity, postural balance or limb kinematics in aquatic enclosures. However, it is difficult to correlate these observed human physiological changes with specific underwater characteristics. The basic understanding of how the different underwater features affect the human physiology is useful to develop appropriate frameworks for training divers to perform submarine tasks. In this research, ground reaction forces, muscular activity and limb coordination are analyzed during reaching movements in this simulated environment and compared with corresponding terrestrial performance. Buoyancy force has a significant effect on the center of mass displacement of the human body outside the current base of support. From the experiments it is observed that the ground reaction forces and the back-muscle activity were reduced during the task in the simulated environment. Results obtained from this testbed show similarities with previous experiments performed in underwater environments and this can provide insights into the influence of aquatic on functional tasks.

Finally, chapter 9 shows the development of the upgraded end-effector aiming to exert the effort to two different limbs to spread the forces applied in different parts. This is useful to simulate the underwater conditions in more than one part of the body increasing the quality of the simulation and reducing the possible pain that a high pressure due to the wrenches could make to human subjects. This device could have the shape of two belts for experiments with humanoids and the control can be done by using the method developed based on the energy.

The experiment to validate the mechanism was performed with the built CDPR with the upgraded end-effector with 2 bodies. The results show a very good repeatability and an acceptable precision for the main body of the end-effector fixed. So, the high-quality tests with the main body of the underwater robot fixed can be performed in order to adjust the forces to maintain the equilibrium or perform basic articulated movements.

9.1.- Future Works

The main work needed to perform is to apply the method developed in this thesis for a moving end-effector. A proposal for this task is an analysis of the Jacobian matrix for each sample and set the appropriate tension distribution for each one. The movement of the underwater robot could be tracked with vision systems to have an accurate Jacobian matrix.

The definition of the underwater environment could be upgraded by adding accurate models of underwater currents, drag forces and added mass effects. Those effects could be applied in different parts of the end-effector and simulate them in the underwater robot.

The method developed for two bodies and 1 inner DoF could be enlarged by adding more actuators able to control a more complex multi-body mechanism with a pattern of distributed wrenches.

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A. APPENDS

A.1. Topology of the feasible elastic energy stored in one cable

Demonstration that the topology of the i -cable energy corresponds to a parabolic cylinder when any two different nullspace variables are considered.

By expressing (4.9) with homogeneous coordinates, the following simplified expression is obtained:

$$(\lambda_h)^T \mathbf{M}_i \lambda_h = 0 \quad (\text{A.1})$$

With

$$\lambda_h = \begin{pmatrix} 1 \\ \lambda_\alpha \\ \lambda_\beta \\ U_i \end{pmatrix} \quad (\text{A.2})$$

$$\mathbf{M}_i = \frac{1}{2k_i} \begin{pmatrix} b_i^2 & b_i a_{i\alpha} & b_i a_{i\beta} & -k_i \\ b_i a_{i\alpha} & a_{i\alpha}^2 & a_{i\alpha} a_{i\beta} & 0 \\ b_i a_{i\beta} & a_{i\alpha} a_{i\beta} & a_{i\beta}^2 & 0 \\ -k_i & 0 & 0 & 0 \end{pmatrix} \quad (\text{A.3})$$

The classification of quadrics is done according their signature, σ , defined as the module of the difference between the number of positive and negative eigenvalues of the adjunct matrix of $\mathbf{M}_{i00}$, defining $\mathbf{M}_{i00}$ as:

$$\mathbf{M}_{i00} = \frac{1}{2k_i} \begin{pmatrix} a_{i\alpha}^2 & a_{i\alpha} a_{i\beta} & 0 \\ a_{i\alpha} a_{i\beta} & a_{i\beta}^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (\text{A.4})$$

The eigenvalues, u , of $\mathbf{M}_{00}$ can be obtained by using the associated invariants:

$$\det(u\mathbf{I}_3) = u^3 - Iu^2 + IIu^3 - III \quad (\text{A.5})$$

With

$$I = a_{i\alpha}^2 + a_{i\beta}^2 + 0 \geq 0 \quad (\text{A.6})$$

$$II = \det \begin{pmatrix} a_{i\alpha}^2 & a_{i\alpha} a_{i\beta} \\ a_{i\alpha} a_{i\beta} & a_{i\beta}^2 \end{pmatrix} + \det \begin{pmatrix} a_{i\alpha}^2 & 0 \\ 0 & 0 \end{pmatrix} + \det \begin{pmatrix} a_{i\beta}^2 & 0 \\ 0 & 0 \end{pmatrix} = 0 \quad (\text{A.7})$$

$$III = \det(\mathbf{M}_{i00}) = 0 \quad (\text{A.8})$$

Considering (4.22), there are two eigenvalues that are equal to zero. The determinant of $\mathbf{M}$ can define the shape of the quadric:

$$\det(\mathbf{M}_i) = k_i \det \begin{pmatrix} b_i a_{i\alpha} & a_{i\alpha}^2 & a_{i\alpha} a_{i\beta} \\ b_i a_{i\beta} & a_{i\alpha} a_{i\beta} & a_{i\beta}^2 \\ -k_i & 0 & 0 \end{pmatrix} = 0 \quad (\text{A.9})$$

$$\det(\mathbf{M}_i) = k_i \det \begin{pmatrix} b_i a_{i\alpha} & a_{i\alpha}^2 & a_{i\alpha} a_{i\beta} \\ b_i a_{i\beta} & a_{i\alpha} a_{i\beta} & a_{i\beta}^2 \\ -k_i & 0 & 0 \end{pmatrix} = 0 \quad (\text{A.10})$$

Because the determinant is null, new invariants need to be introduced:

$$II' = \det \begin{pmatrix} b_i^2 & b_i a_{i\alpha} \\ b_i a_{i\alpha} & a_{i\alpha}^2 \end{pmatrix} = 0 \quad (\text{A.11})$$

$$III' = \det(\mathbf{M}_{i11}) + \det(\mathbf{M}_{i22}) + \det(\mathbf{M}_{i33}) = -k_i(a_{i\alpha}^2 + a_{i\beta}^2) \leq 0 \quad (\text{A.12})$$

The value of II is zero and III' is less or equal to zero, so the shape of the quadric that corresponds to the potential energy stored in the cable in function of two nullspace variables is a parabolic cylinder.

A.2.- Topology of the feasible elastic energy stored in all the cables

Demonstration that the topology of the total energy stored in all cables corresponds to an elliptic paraboloid when any two different nullspace variables are considered.

A similar method to that described in the previous section is used. The equation with homogeneous coordinates is

$$(\lambda_h^*)^T \mathbf{M} \lambda_h^* = 0 \quad (\text{A.13})$$

With

$$\lambda_h^* = \begin{pmatrix} 1 \\ \lambda_\alpha \\ \lambda_\beta \\ U \end{pmatrix} \quad (\text{A.14})$$

$$\mathbf{M} = \sum_{i=1}^m \mathbf{M}_i \quad (\text{A.15})$$

The invariants are

$$I = \sum \frac{a_{i\alpha}^2}{2k_i} + \sum \frac{a_{i\beta}^2}{2k_i} + 0 > 0 \quad (\text{A.16})$$

$$II = \det \begin{pmatrix} \sum \frac{a_{i\alpha}^2}{2k_i} & \sum \frac{a_{i\alpha} a_{i\beta}}{2k_i} \\ \sum \frac{a_{i\alpha} a_{i\beta}}{2k_i} & \sum \frac{a_{i\beta}^2}{2k_i} \end{pmatrix} = 0 \quad (\text{A.17})$$

$$III = \det(\mathbf{M}_{00}) = 0 \quad (\text{A.18})$$

The determinant of $\mathbf{M}$ is

$$\det(\mathbf{M}) = \det \begin{pmatrix} \sum \frac{b_i a_{i\alpha}}{2k_i} & \sum \frac{a_{i\alpha}^2}{2k_i} & \sum \frac{a_{i\alpha} a_{i\beta}}{2k_i} \\ \sum \frac{b_i a_{i\beta}}{2k_i} & \sum \frac{a_{i\alpha} a_{i\beta}}{2k_i} & \sum \frac{a_{i\beta}^2}{2k_i} \\ -\frac{1}{2} & 0 & 0 \end{pmatrix} = \frac{1}{2} \left(\left(\sum \frac{a_{i\alpha} a_{i\beta}}{2k_i} \right)^2 - \sum \frac{a_{i\alpha}^2}{2k_i} \sum \frac{a_{i\beta}^2}{2k_i} \right) \neq 0 \quad (\text{A.19})$$

In order to classify the quadric, it is necessary to know the sign of the $\det(\mathbf{M})$. It only can be zero if $a_{i\alpha} = a_{i\beta}$. This condition is never achieved because the kernel of $\mathbf{A}$ cannot lose rank, considering the rank-nullity theorem (Alama, 2007). Thus, because $\text{III} = 0$ and $\text{I} > 0$, the shape of the total energy space when varying two nullspace variables is an elliptic paraboloid.