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**Design and Control of a Transformable
Anthropoid Robot for Underwater Works**

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*A mis padres
y a Inma*

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Resumen

Los trabajos submarinos realizados en estructuras sumergidas requieren dispositivos para el manejo de equipos y herramientas tanto en aplicaciones offshore como de interior. Los vehículos submarinos teledirigidos se han utilizado durante décadas para realizar operaciones submarinas con cierto grado de telepresencia, utilizando uno o más manipuladores. Sin embargo, cuando las tareas se tornan complejas es necesaria la inmersión humana. Aparte de los riesgos para la salud relacionados con la presión, existen una serie de peligros asociados a los trabajos realizados en ambientes submarinos hostiles. Además, dichos trabajos solo son posibles mediante el uso de máquinas a partir de cierta profundidad.

Este trabajo de investigación se basa en la idea de que la robótica humanoide puede contribuir considerablemente a solventar estos problemas, proporcionando buzos robotizados para trabajos submarinos peligrosos. Como prueba de concepto, un novedoso robot humanoide submarino llamado DiverBot se desarrolla a lo largo de esta tesis, haciendo hincapié en aspectos de diseño y control.

El diseño del robot se inspira en las proporciones de los chimpancés y presenta la capacidad de transformarse entre dos modos funcionales diferentes *i.e.*, modo antropeide y modo vehículo. Los brazos y piernas del robot son movidos por accionamientos hidráulicos, mientras que el robot es impulsado mediante propulsores eléctricos. Un sistema software es implementado mediante un controlador de tiempo real para la gestión de sensores y accionamientos del robot. Se propone un análisis de estabilidad estática para la locomoción cuadrúpeda en condiciones submarinas basado en un método de la teoría de torsos. El problema de regulación de consigna en modo vehículo se resuelve mediante un esquema de control basado en asignación óptima de errores y controladores lineales.

Los resultados experimentales muestran un correcto funcionamiento del prototipo en condiciones reales, abriendo nuevos horizontes a futuras aplicaciones en tareas cada vez más complejas. En este sentido, los buzos robotizados podrían ser una nueva generación de máquinas para trabajos submarinos y su desarrollo será, sin duda, uno de los retos de la robótica aplicada en los próximos años.

Abstract

The underwater works performed on submerged structures require devices for handling equipment and tools in both offshore and inland applications. Remotely operated vehicles have been used since decades to perform underwater operations with some degree of telepresence, using one or more manipulators. However, when the tasks become complex human immersion is needed. Apart from the health hazards related with pressure, there exists a number of risks associated to operations realized in hostile underwater environments. Moreover, beyond certain depth underwater works are not possible for humans without using machines.

This research work builds on the idea that humanoid robotics can broadly contribute to solve this problem, providing robotic divers for dangerous underwater works. As a proof of concept, a novel underwater humanoid robot named DiverBot is developed along this thesis, focusing on design and control aspects.

Robot design is inspired by the proportions of chimpanzees, and presents the capability to transform between two different functional configurations *i.e.*, anthropoid and vehicle modes. The arms and legs of the underwater robot are driven by hydraulic actuators, while electric thrusters are used for propulsion. A software system is implemented using a real-time controller to manage the sensors and actuators of DiverBot. A static stability analysis is proposed for quadrupedal locomotion in underwater conditions based on a screw theory method. The set-point regulation problem is solved for vehicle configurations by means of a control strategy based on optimal allocation of errors and linear controllers.

The experimental results show a correct performance of the prototype in underwater conditions, opening new horizons to potential applications of DiverBot for increasingly complex missions. In this way, robotic divers could be the next generation of machines for underwater works, and its development will be certainly one of the challenges of applied robotics in the coming years.

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*In the twenty-first century, the robot will
take the place which slave labor occupied
in ancient civilization.*

Nikola Tesla

Chapter 1

Introduction

Underwater technology enables humans to attain the depth of oceans and lakes of the world. Remotely operated vehicles have been used since decades to perform increasingly complex underwater works, such as object recovering or operating valves on submerged structures using one or more manipulators. This research is based on the idea that humanoid robots can be adapted to work at these environments, naturally harmful for people, working under water as robotic divers. This first chapter provides the motivation for this research work. The aims and limits along with the original contributions of this research are described. Finally, the structure of this document is outlined in the last section.

1.1 Motivation

Since ancient times, men have shown interest in developing machines capable to mimic the motion of animals and humans *i.e.*, *automatons*. Nevertheless, is not until 1920 when the word *robot* is used for the first time in a science fiction play by Czech writer Karel Čapek to describe a machine that performs forced works.

1. Introduction

In the last decades, robots have moved to the real world and several works which are repetitive or dangerous for humans are gradually performed by robots. In the case of underwater applications, the development of underwater robots to navigate and carry out exploration and manipulation in the vast environment of marine waters has been widely investigated for years and can be considered to be a mature technology, but currently faces complex problems with their autonomy, manipulation, perception and communication (Zhang et al., 2015).

As is the case in the oil and gas industry, remotely operated vehicles (ROV) have been used since decades in assisting such activities, working at greater depths than divers can nowadays attain (Stavinoha et al., 2014). However, when the complexity of the task is elevated, human intervention is needed.

People working on the professional diving sector are specialized on underwater operations requiring physical interaction in both offshore and inland applications. Apart from the health injuries related with immersion, there are a number of risks associated to the works realized in underwater environments, that expose divers to lethal risks and harmful phenomena (see Section 2.2).

From the accidents produced by the use of hydraulic tools in offshore platforms to the radiation exposure that nuclear divers undergo in nuclear reactors, are enough to motivate the development of underwater robots to assume the risks related with such hostile environments. There exists a strong necessity of underwater works. However, there is no device which combines the capabilities of ROV and divers to perform these tasks without need human immersion.

Humanoid robots are broadly evolved in the last years. Recent developments focus on potential applications in real scenarios *e.g.*, factories (Guizzo, 2011) and space exploration activities (Stoica and Keymeulen, 2006).

In this line, humanoid robotics can also contribute to underwater technology, providing remotely controlled humanoid robots for operations in hostile underwater environments. Thus, *robotic divers* could be the next generation of machines for dangerous underwater operations.

Such devices could contribute technological advantages to perform underwater works; not only in oil and gas industry and inland applications, but also in the rising sectors as deep sea mining and offshore wind power generation.

1.2 Objectives

This thesis builds on the idea that humanoid robots can be excellent candidates to perform underwater works in places which are noxious or dangerous for humans. As a first step towards this direction, this research work is developed around the design and control of a novel underwater humanoid robot, in order to provide a proof of concept of such idea by means of a functional prototype. The following objectives are included within the framework of this thesis:

- *To design an underwater robot with anthropoid structure.* Along this document, the underwater robot is described as an anthropoid robot instead of a humanoid robot. The aim is to specify that the developed robot can share features own of apes, which allow to have good mobility conditions while keeping an intuitive architecture for human operators.
- *To design a robot capable to configure as an underwater vehicle.* The anthropoid robot can be configured as a remotely operated vehicle. The interest of such configuration is to minimize the energy required for long distance displacements, as well as to take advantage of the existing equipments for these devices *e.g.*, tether management systems.
- *To develop a control software for teleoperation.* The software system allows to manage sensors and actuators of the robot from a control station through an umbilical cable. Teleoperation plays an important role as increases the intelligence by putting a human in the control loop, which constitutes an advantage for tasks requiring a high degree of adaptability.
- *To fabricate and evaluate the robot prototype.* The robot prototype is fabricated using materials resistant to water corrosion, and it is tested in laboratory conditions *i.e.*, calm and shallow waters. The transformation between anthropoid and vehicle configurations as well as the trim of the system buoyancy are carried out before immersion.
- *To analyse and implement motion strategies for underwater locomotion.* Quadrupedal locomotion can be realized using the anthropoid structure of

1. Introduction

the robot. The interest is to perform a task requiring the control of all robot joints simultaneously without neglecting system stability. These motion strategies can also be used for other underwater tasks.

- *To study and implement a control strategy for vehicle maneuvers.* For long distance displacements, the vehicle configuration offers minimum drag forces resisting robot motion. Hence, results interesting to implement an algorithm to control the robot motion in such configuration. The control strategy must adapt to manual commands and possible changes on the robot prototype.
- *To validate developed models against experimental data.* The performance of the robot prototype together with the motion strategies developed for quadrupedal locomotion and the control scheme proposed for vehicle maneuvers, must be experimentally validated. Experimental results are discussed and improvements for the developed models are pointed out.

1.3 Contributions

Along this research several topics have been addressed in the fields of design and control of underwater robots. The main contributions of this work include:

- *Design and development of a novel underwater anthropoid robot.* The mechatronic design is carried out using a modular approach. The robot structure is inspired in the proportions of chimpanzees with the additional capability to transform into a remotely operated vehicle. A real prototype of the robot, named DiverBot, is fabricated. These particular features as well as the modular design approach have resulted in two invention patents.
- *Design of a novel parallel current meter.* The concept design and calculation methodology of an instrument for measuring fluid currents is proposed as part of the sensory system of the robot. The instrument is intended for measuring disturbances produced by water currents, based on a spherical parallel mechanism that reacts to drag forces exerted by the fluid on a spherical body. These specific features have resulted in a patent.

- *Implementation of a control software for teleoperation.* The underwater robot includes an on-board programmable automation controller connected to several sensors and actuators. Embedded software and high level software is developed and tested in actual operating conditions in order to manage sensors and actuators of the DiverBot prototype from a user interface.
- *Stability analysis and control for underwater locomotion.* Quadrupedal locomotion is analysed as a robust strategy for short distance displacements in general terrains. A method based on screw theory is applied to measure static stability considering underwater conditions. Joint-space position control is implemented through several linear controllers. The proposed models are implemented as part of the software system of DiverBot.
- *Development of a control strategy for maneuvers in vehicle mode.* The underwater robot can be configured as a remotely operated vehicle to displace through the water using multiple thrusters. Thus, a control scheme based on robot geometry is implemented including manual commands. The developed models are integrated into the software system of DiverBot.
- *Experimental validation of the underwater robot.* A series of preliminary experiments have been carried to evaluate the performance of the developed prototype. The proposed control schemes are also tested to demonstrate the features related to the robot locomotion in anthropoid mode and displacements through the water under vehicle configuration.

These contributions had led to scientific publications, including JCR journals, patents, book chapters, and press articles, which are listed in Appendix A.

1.4 Outline

The remainder of this document is organized as follows. Chapter 2 highlights the risks involved with diving activities developed by human divers, in both offshore and inland applications. This chapter presents some underwater devices used for works on submerged structures and addresses recent developments of anthropomorphic robots designed to work as robotic divers.

1. Introduction

Design aspects of the underwater anthropoid robot are presented in two chapters. Chapter 3 focus on the hardware system of the robot. Geometrical proportions and the capability to transform between two functional modes are described (*i.e.*, anthropoid and vehicle modes). Subsystems and mechanisms forming the robot are analysed and integrated into a real prototype. The developed software for handling the sensors and actuators of the DiverBot prototype is presented in Chapter 4, resulting in a user interface for robot teleoperation.

Control aspects related with the functional modes of the robot are treated along two chapters. In Chapter 5 a screw-based method is implemented under reduced gravity conditions to determine the static stability during quadrupedal locomotion in underwater terrains. Chapter 6 solves the setpoint regulation problem based on robot geometry and linear controllers. The obtained control scheme is intended for long distance displacements under vehicle configuration.

The developed prototype together with the control software implemented in these chapters are tested in actual operating conditions to validate the performance of DiverBot. Chapter 7 presents the results obtained from these experiments. Finally, conclusions and future works are given in Chapter 8.

*Even though the future seems far away,
it is actually beginning right now.*

Matthew Stepanek

Chapter 2

State of the Art: Robotic Divers for Underwater Works

This chapter addresses recent developments of human-like robots designed to work as robotic divers, assuming complex and hazardous activities currently carried out by human divers in hostile underwater environments. The risks involved in the most dangerous branches of the professional diving industry are highlighted. Current devices used in underwater operations are described *i.e.*, manned and unmanned underwater vehicles. Finally, a background of robotic divers under development for underwater operations is presented.

2.1 Introduction

The motivation for this research work is succinctly exposed in the previous chapter, standing out a strong necessity of underwater devices to avoid the hazards associated with the operations carried out by human divers. Along this chapter, the risks involved in dangerous diving activities are mentioned, and the current technologies used to extend human capabilities are described. Future challenges

2. State of the Art: Robotic Divers for Underwater Works

on robotics include the development of advanced robots for underwater interventions, thus, recent developments of robotic divers are addressed.

This chapter is structured as follows. Section 2.2 describes the risks implied in some of the most dangerous diving activities. Section 2.3 presents the current technologies to assist divers in carrying out underwater operations. Section 2.4 collects recent advances on robotic divers from the academic and industrial world. Finally, the conclusions of this chapter are summarized in Section 2.5.

2.2 Risks Associated with Diving Operations

Apart from the health hazards derived from diving activities *e.g.*, decompression illness, pulmonary barotrauma, nitrogen narcosis (Council, 2009), there exist several risks associated with the works performed by human divers. The professional diving sector include several dangerous works, some of them are presented in the following sections in order to emphasize the need of technological developments for supporting commercial and scientific operations.

2.2.1 Offshore Diving

The offshore oil and gas industry as well as the prominent offshore wind power sector, require commercial divers to perform underwater operations for construction and maintenance of submerged structures (see, Figure 2.1).

Scuba divers carry out inspection tasks in areas of good visibility up to 70 meters depth; despite of having good mobility, they are limited in communication and capabilities for using tools. On the other hand, saturation divers can perform underwater construction and maintenance tasks at more than 300 meters depth using a mixture of oxygen and inert gases, wearing hard helmets and full body suits to protect against abrasion, puncture or debris. When working on cold waters, tethered divers can control its temperature by means of drysuits outfitted with warm water circulation. Further, they have fiber optic communication and hydraulic lines to power several tools (Gerwick, 2007).

One important limitation of divers is the difficulty in determining its own position, because water pressure affects human sensory and reasoning capabilities,

2.2 Risks Associated with Diving Operations

Figure 2.1: Typical offshore diving operations, (a) pipeline welding, and (b) cleaning a structure using abrasive tools.

and produces disorientation and loss of reference planes. Also, speaking intelligibility is reduced due to the breathing gas mixture. All this facts increase the risk of physical fatigue and stress.

The capacity of divers to apply forces is limited by buoyancy forces, then, several means of attachment and hydraulic tools have been developed to assist divers in their works. Marine currents tend to displace divers away from their working position, while marine growth can rip their suits. Besides, the diver is exposed to noise, electrical shocks, debris, and also accidents related with the use of tools *e.g.*, water jetting at high pressure, hydraulic cutting, or welding.

2.2.2 HazMat Diving

As can be seen in Figure 2.2, hazardous material (HazMat) divers deals with diving operations in highly contaminated environments, such as sewage treatment plants, septic tanks or polluted waters (US-Navy, 2008).

HazMat divers are prepared to enter these environments and complete different tasks including: installation and maintenance of gates and valves, inspection of areas with zero visibility, pollution control, measurements and sampling activities. Nevertheless, they are highly exposed in such environments.

For instance, sewage divers risk to contract diseases through cuts and punctures due to the presence of sharp objects in the raw sewage, such as broken glass

2. State of the Art: Robotic Divers for Underwater Works

Figure 2.2: Hazardous materials diving, (a) sewage diver, (b) working on contaminated groundwaters, (c) drysuit after immersion in toxic water, and (d) decontamination process.

and hypodermic needles. Due to the turbidity of water, light levels are often very low and the divers must rely on its touch sense to be guided.

HazMat divers wear a full drysuit with a rigid helmet, boots and cut-resistant gloves directly sealed to the suit. The drysuit is pressurized with breathing gas to prevent the ingress of liquid in case of a puncture, and must be made from a material resistant to the hazardous materials present at the site.

Furthermore, full decontamination equipment is required when the operation is completed (Figure 2.2.d), emergency procedures must be planned, and equipment and personnel must be in place to recover the diver in case of accident.

2.2.3 Nuclear Diving

As shown in Figure 2.3, nuclear divers work at the water-filled fuel pools of nuclear power reactors performing several operations, such as replacing sensors into the

2.2 Risks Associated with Diving Operations

Figure 2.3: Nuclear diving, (a) inspection tasks inside a fuel pool, (b) a diver coming out of a nuclear reactor.

fuel transfer canals, recover lost items which could damage the fuel rods, or welding on cracked steam dryers (Sheafer, 2011).

Nuclear diving is a strong necessity for nuclear plants each time an operation is needed on the reactor, especially when emergencies occur. A dive is preferred instead of draining the entire pool to perform an operation that would be costly, producing a hazardous exposure for the rest of workers, and also because million of dollars are lost for each day the plant is not producing power.

To control the radiation exposure, nuclear divers have to use special equipment. Several electronic dosimeters, which are monitored, are used to record the amount of received radiation at different parts of the body. Also, a portable dosimeter allows the diver to detect radiation sources during the dive.

Apart from radiation, nuclear divers are exposed to heat stress since the water temperature inside the pool is approximately at 35 degrees Celsius. For long time immersions, a tethered cold water suit should be used. The hands are covered with rubber gloves and the head is covered with a positive pressure helmet.

Once the operation is completed all the tools and equipment are brought to the surface to be rinsed with demineralized water and wiped down by the dive crew. Then, the umbilical and the diver must be thoroughly cleaned. When the cleaning process is concluded, the personnel must ensure there is no imperceptible irradiated material using radiation meters.

2.3 Current Devices for Underwater Operations

Beyond certain depth underwater works become impossible for humans without using machines. Several underwater vehicles have been developed in the last decades to supplement divers in their underwater activities. The following sections present two of the most used devices for underwater interventions.

2.3.1 ROV: Remotely Operated Vehicle

A Remotely Operated Vehicle (ROV) is an unmanned underwater vehicle connected to a mothership through an umbilical cable and controlled by a pilot. The umbilical transmits power and commands to the vehicle propulsion system, and sends back data *e.g.*, audio, video, or other sensor readings (Moore et al., 2010).

The size of an ROV can range from small vehicles of a few kilograms to large units weighing many tons. Observation class ROVs are mainly used for scientific purposes, or inspection tasks in hazardous or confined environments, while the work class ROVs are preferred when underwater works are required.

The offshore oil and gas industry implements large work class ROVs, which are usually outfitted with two manipulators with multiple *degrees of freedom* (DOF) and interchangeable tools *e.g.*, jet cleaning equipment or sampling devices. Work class ROVs are used for operating on seabed facilities and maintaining underwater components of oil rigs, or underwater pipelines (see, Figure 2.4).

Figure 2.4: Remotely operated vehicles, (a) Seaeye Leopard equipped with two manipulators, (b) a work class ROV working subsea.

2.3 Current Devices for Underwater Operations

Many ROVs implement depth and heading autopilots, which rely on computers to monitor vehicle sensors and automatically adjust thrusters to hold the vehicle in a particular location *i.e.*, position-keeping. This frees the pilot to focus on other tasks such as using the manipulators for handling tools. For deepwater facilities, these vehicles are the only developed tool since they are capable of working at thousands of meters depth (Gerwick, 2007).

Before the advent of ROV technology to the offshore industry, in situations that divers could not perform a task for any number of reasons, the items had to be dismantled and pulled out to be repaired. Nowadays, because of the proven reliability and capability of ROVs, subsea portions of the offshore projects are designed strictly around its capabilities (Lay, 2015).

There exist numerous offshore structures that were built before the use of ROVs, and thus maintenance must be carried out by a diver. Divers are more flexible for completing tasks, and sometimes more economical. Moreover, for certain tasks an ROV has limited dexterity on its manipulators, whereas a diver can be pretty dexterous. The diver adapts better to unforeseen changes in the operation, whereas with an ROV is more difficult (Lay, 2015).

2.3.2 ADS: Atmospheric Diving Suit

An Atmospheric Diving Suit (ADS) is a pressure resistant suit made with rigid hulls articulated with special watertight joints, to protect the diver from exposure to extreme pressures. These special suits can attain up to 600 meters depth, while keeping the internal pressure close to one atmosphere (Thornton, 2000).

The ADSs are equipped with thrusters for independent mobility and two grippers operated by the diver, using its hands and arms to perform underwater tasks (see, Figure 2.5). The ADSs are used for deep-water operations in the offshore oil and gas fields, and also for military purposes worldwide.

The main advantage of the ADS is the absence of physiological hazards produced by water pressure. There is no need of decompression, and no danger of nitrogen narcosis because the pilot is breathing air at atmospheric pressure (Lay, 2013). Compared with saturation divers, the atmospheric diving suit can perform multiple changes in depth without any consequences or delay. Communications

2. State of the Art: Robotic Divers for Underwater Works

Figure 2.5: Atmospheric diving suits, (a) Exosuit before an immersion, (b) Hardsuit operating under water.

with a saturation diver are highly distorted due to the helium effect on its vocal cords, whereas communicating with an ADS pilot is similar to having a phone conversation (Lay, 2013).

However, a diver using an ADS loses the human sense of touch and the grippers provide only 75% of the dexterity of a traditional diver. Hence, there is a difficulty involved in executing tasks requiring a significant manual dexterity. Additionally, ADS are bulky and may cause maneuverability problems for accessing confined spaces (Lay, 2013), (Gerwick, 2007).

2.4 Recent Developments of Robotic Divers

Despite of the extensive development of human-like robots for land (Cass, 2013), (Sakagami et al., 2002) and space applications (Diftler et al., 2011), humanoid robots for underwater applications are scarce and almost all the available records refers to conceptual ideas not yet realized.

The following sections describe the state of the art of humanoid robots designed specifically for underwater environments. Some of them were found in the literature during the robot design process, while the last two were encountered from an international search report obtained during the patent process of the anthropoid robot developed in this research work.

Figure 2.6: The robotic platform OceanOne, (a) underwater manipulation tests in a swimming-pool, (b) first immersion at La Lune on the southern coast of France, in collaboration with DRASSM.

2.4.1 Robotic Explorer OceanOne

Stanford University and King Abdullah University of Science and Technology (KAUST), together with Meka Robotics (currently acquired by Google) are collaborating since 2012, on the development of a new underwater robot to help marine scientists in the exploration of the fragile ecosystem of the Red Sea.

The underwater robot depicted in Figure 2.6 is still under development, and combines a thruster-actuated vehicle with two lightweight arms and compliant hands, to perform fine and dexterous tasks (Murphy, 2015).

The robot arms have 7-DOF each, and are almost like the human arm in terms of mobility. The hands, provided with tactile sensing, can reconfigure to grasp large or small objects, while the tactile perception allows the operator to detect slippage and texture of the object being manipulated (Khatib, 2015).

The body of the underwater explorer is outfitted with 8 thrusters for underwater displacement. Over its backs, the electronics for processing, perception, and sensing capabilities are placed inside a black pressure canister. On the back, the batteries are contained in a cylindrical waterproof package.

In order to reach deep waters the robotic diver is constructed as an oil filled system. The prototype is intended to reach up to 300 meters depth with 1 hour of autonomy. The whole system needs to be close to neutral buoyancy, to minimize the energy required by the propulsion system (Ackerman, 2016).

2. State of the Art: Robotic Divers for Underwater Works

A teleoperation interface will be used to remotely operate the robot, which comprises a 3D vision system for visual feedback and two high bandwidth haptic devices providing force-feedback guidance to the operator. This allows to use the underwater robot for bimanual haptic telemanipulation. Additionally, the robot will have autonomous skills, such as position keeping and obstacle avoidance.

2.4.2 Humanoid ROV Poseidon

The underwater robot Poseidon was developed at the Hong Kong University of Science and Technology (HKUST) for the 2012 MATE International ROV Competition. The robot was inspired on the atmospheric suits and is described in (Woo et al., 2012) as an ROV with anthropomorphic structure (see, Figure 2.7).

The prototype is equipped with stereo vision, two 6-DOF arms, inertial sensors, four electric thrusters, and two caterpillar treads for displacements on the seabed. The arms are moved by waterproof servomotors, and are equipped with grippers which are used to grab and place items under water.

Poseidon can track the operator motion by means of a telemetry suit, being an intuitive teleoperation system. The suit uses encoders for taking measures of the operator motion and is provided with two joysticks to control the grippers of the robot. At the same time, the pilot can observe on a head-mounted display the 3D images provided by the stereo vision system mounted on the robot head, which improves depth perception in manipulation tasks.

Figure 2.7: Humanoid ROV Poseidon, (a) final prototype, (b) inside a pool for the 2012 MATE ROV competition.

2.4.3 Submerged Inspection and Working Robot

A humanoid robot for underwater working and inspection of underwater structures is presented in the Japanese patent JPH08240689 (see, Figure 2.8). The invention describes a device in which an underwater inspection apparatus and an underwater working apparatus are integrated into a single robot. Accordingly, the waiting time during an operation is reduced, because a single device can perform both inspection and working tasks. Its working accuracy is high, and consequently its working time is short compared with others devices.

Figure 2.8: Diagrams from the Patent JPH08240689 (Applicant: Mitsubishi Heavy Industries Ltd. - 1996).

The underwater humanoid robot is equipped with two legs (4) with multiple joints, each comprising suction cups (5) at their lower ends, with a trunk (2) comprising six screw-propeller thrusters (6a) to (6f) which can generate variable thrust forces in all directions in cooperation with each other, with two arms (1) with multiple joints, each comprising at least two fingers (3) at their tip and with a head ballast tank (8) in which a visual observation device with a concentrated monitoring mechanism and a pan and tilt mechanism is arranged and installed inside a transparent tank (Nagaoka et al., 1996).

2.4.4 Underwater Work Robot

The robot depicted in Figure 2.9 belongs to the Japanese patent JPS6116192. The purpose of the invention is an underwater working robot to operate in narrow spaces by means of a head having sensors and manipulators for handling objects, which is installed on the end of a neck, extensible along the longitudinal direction of the body of said underwater robot (Hirabayashi et al., 1986).

Figure 2.9: Diagrams from the Patent JPS6116192
(Applicant: Kogyo Gijutsuin - 1986).

The underwater robot is constituted of a body (1), and a head (2) mounted on the front part of the body (1), a variable vector propeller (3) used as propelling device, two front legs (4) and a rear leg (7), and two manipulators (9) installed on the head (2). A neck (18) supports the head (2) and is telescopically extensible in the axial direction. The manipulator (9) has several jointed fingers and a pressure sensor provided on the tip of every finger to detect pressure when an object is grasped and to control the movement of the finger. The neck (18) can be retracted to bring the head (2) close to the body (1), enabling underwater TV cameras (15) and (11) to be housed in the body (1) and head (2), respectively. The front leg (4) is provided with fasteners (5) and a support bar (6), while the rear leg (7) is only equipped with a rear fastener (8).

2.5 Conclusion

The aim of this chapter has been to contextualize the necessity of novel underwater robots for works requiring physical intervention, referencing recent developments of robotic divers. These robots are designed to assume the risks associated with professional diving activities, carried out by human divers working in hostile underwater environments at limited depths.

There is a strong necessity of underwater works, but most of the available tools are prepared just for inspection tasks. ROV and ADS have already had decades of evolution and have proven to be useful technologies for working at greater depths. Nevertheless, they lack human dexterity, which is very important for performing complex underwater tasks such as welding, assembling and repairs.

Humanoid robotics can broadly contribute to this problem, providing human-like robots for underwater works. The robotic platform OceanOne is currently under development and promises interesting results, while there is no evidence that the robots of the patent proposals have been materialized so far.

Robotic divers could be the next generation of machines for underwater interventions, and the development of underwater humanoid robots will be certainly one of the challenges of applied robotics in the coming years. In this way, design and development of a novel underwater anthropoid robot, specially adapted for underwater works, will be addressed in the next chapters.

2. State of the Art: Robotic Divers for Underwater Works

*It is through science that we prove, but
through intuition that we discover.*

Henri Poincaré

Chapter 3

Hardware Architecture of an Underwater Anthropoid Robot

This chapter presents the design and fabrication of a hydraulic underwater robot with anthropoid structure, which can be transformed into a remotely operated vehicle. The underwater robot is prepared to displace through the water as a vehicle, and perform physical operations as a robotic diver. The design requirements are defined, the geometric proportions of the robot are presented, and its functional modes are introduced. The hardware design is described along four parts, including the design of robot head and torso, an underwater control unit, hydraulic arms and legs, and anthropomorphic hands. Finally, a functional prototype is presented and the conclusions of the chapter are outlined.

3.1 Introduction

In the previous chapter, the risks associated with professional diving activities are presented. The necessity of robotic divers specially adapted for underwater operations is introduced, and recent developments on this subject are addressed.

3. Hardware Architecture of an Underwater Anthropoid Robot

The focus of this chapter is on hardware design and fabrication of an underwater robot with anthropoid structure, which can be remotely operated with a certain degree of autonomy to realize physical interventions under water as a robotic diver. Also, the anthropoid robot is designed to transform into a remotely operated vehicle to facilitate the displacement beneath the water surface.

The technical plausibility of the proposed robotic diver can be proved by developing a first functional prototype. The robot design is a challenge in itself: a high number of custom parts, sensors and actuators, as well as flotation and propulsion systems must be correctly integrated to control the system. The mechanical and electronic design of the underwater robot is presented in this chapter as the basis for software and control schemes presented in the subsequent chapters.

Section 3.2 defines the design requirements, presents the robot proportions, and describes the functional modes of the system. The design of robot head and torso is described in Section 3.3, including ballast and propulsion systems, and a device for water current measurements. The electrical and hydraulic elements that compose the underwater control unit are presented in Section 3.4. Section 3.5 treats the design of hydraulic fore and rear limbs. The robotic hands are depicted in Section 3.6, highlighting its main features and functionalities.

The assembled control unit is shown in Section 3.7. The robot prototype and important milestones achieved during hardware development are shown in Section 3.8. Conclusions of this chapter are outlined in Section 3.9.

3.2 Design Requirements

The robotic diver is treated as a mechatronic system that integrates different components and technologies. The system is partitioned into a part implemented in hardware and a part implemented in software, according to the concepts presented in guideline VDI2206 “Design methodology for mechatronic systems” (VDI, 2004).

The overall function of the robot is to realize displacements and physical interventions under water, according to the instructions of a human pilot. The robot presents an anthropomorphic structure and includes certain degree of autonomy, to facilitate remote operation. The interest of such system is to assume the risks involved in the professional diving activities mentioned in Chapter 2.

3.2 Design Requirements

Table 3.1: Design requirements of the hardware subsystems.

Module	Description
Head	Implements lighting elements and high level sensory functions, such as image acquisition. It can include lighting elements.
Torso	Supports the limbs and head of the robot as well as the underwater control unit (UCU). Provides sensors and actuators to orientate the limbs and head, as required. Implements propulsion and ballast components. The ballast system must be easily modified to adapt to prototype changes. The propulsion system must have enough power to move the robot at moderate or low speeds.
UCU	Controls the joints and propulsion of the robot. Protects the components susceptible to damage due to contact with water, such as controllers, sensors, and other non-waterproof elements. Provides the data and energy connections to all sensors and actuators, and links the robot to a mothership through an umbilical cable which provides power supply and data communications.
Arm	Supports the weight of the robot under water plus an extra payload and implements lighting elements. The arms have enough degrees of freedom (DOF) to perform simple manipulation tasks, quadrupedal walking, or climbing under water.
Hand	Presents an anthropomorphic structure, allowing an intuitive control by a human operator, to handle standard tools or equipment. It can be capable to grasp objects of different size using a minimum number of actuators. It must be robust enough for use in quadrupedal walking, or climbing under water.
Leg	Supports the weight of the robot under water plus an extra payload. The legs have enough degrees of freedom for quadrupedal walking, or climbing under water. It can optionally implement, grippers in place of foot to facilitate climbing and fastening functions, as well as lighting elements.

The hardware system is divided into six modules or functional units performing different parts of the overall function. Such parts serve to define the design requirements of each subsystem, as summarized in Table 3.1. General requirements for the underwater robot are listed in Table 3.2.

3. Hardware Architecture of an Underwater Anthropoid Robot

Table 3.2: Design requirements of the hardware system.

No.	Description
1	The underwater robot uses hydraulic actuators and electric thrusters, and can be remotely operated through an umbilical cable.
2	The modules of the robot must be prepared for underwater operation in terms of materials and components.
3	The robot structure is dimensioned according to the anthropoid proportions presented in Section 3.2.1.
4	The robot must be capable to configure or transform into different functional modes described in Section 3.2.2.

3.2.1 Anthropoid Proportions

As shown in Figure 3.1, the robot is designed with geometric proportions similar to those found in *Pan troglodytes* (*i.e.*, chimpanzees). Within the suborder of Anthropoidea, these primates can move on four limbs in unstructured environments, and present suitable capacities to perform manual tasks requiring dexterity and accuracy. Recent developments of robots with anthropoid geometry can be found in (Weiguo et al., 2004), (Kühn et al., 2009), and (Fondahl et al., 2012).

Figure 3.1: *Pan troglodytes* skeleton in a quadrupedal pose (a), and schematic view of the underwater anthropoid robot (b).

3.2 Design Requirements

Table 3.3: Robot dimensions based on Pan troglodytes proportions.

segment	parameter	proportion ($d=500\text{mm}$)	calculated value (mm)	selected value (mm)
head	d_1	$0.8 d$	400	400
torso	d_2	$1.9 d$	950	955
upper-arm	d_3	d	500	500
forearm	d_4	d	500	580
hand	d_5	$0.8 d$	400	240
thigh	d_6	d	500	500
calf	d_7	$0.7 d$	350	500
foot	d_8	$0.8 d$	400	300

The interest of having an underwater robot with anthropoid structure lies on the stability of quadrupedal locomotion and the versatility for climbing and grasping objects. An anthropomorphic architecture adapts for human made facilities or tools and encourages intuitive teleoperation methods.

Proportions of the body segments are extracted from (Schoonaert et al., 2007) and calculated for the links of the underwater robot (see, Table 3.3). The robot joints, pointed out on Figure 3.1, are described in Table 3.4.

Length parameters d_i are normalized for an upper-arm length of 500mm, yielding a robot of around 1.6m height in quadrupedal configuration, with an estimated maximum weight in air of 200kg. Hence, the underwater robot in vehicle configuration (Section 3.2.2) is expected to have the size and weight of a small work-class ROV, compared with commercial underwater vehicles.

Table 3.4: Notation for rotational joints with hydraulic actuation.

joint	DOF	parameter	joint	DOF	parameter
neck	1	N	hand	1	G
shoulder	2	S, R	hip	2	V, H
elbow	1	E	knee	1	K
wrist	3	C, W, T	ankle	1	A

Total active DOF: 19 (C and W are passive joints).

3. Hardware Architecture of an Underwater Anthropoid Robot

3.2.2 Anthropoid and Vehicle Modes

As depicted in Figure 3.2, the underwater robot is designed with the capability to transform between two different configurations or modes *i.e.*, anthropoid mode and vehicle mode. The interest of having a system with different functional modes lies in the specific advantages of each configuration.

The robot in anthropoid mode can be remotely operated by one or more pilots, to perform physical interventions under water. Being that the robot and human pilot have similar kinematic structures, the robot can be intuitively controlled *e.g.*, using exoskeletons or motion capture systems. Short-distance displacements are also possible, by using the arms and legs for climbing or walking in reduced space environments, where the use of propellers is impractical or risky.

Figure 3.2: Schematic views of the underwater robot in different configurations, (a) vehicle mode, (b) transition, and (c) anthropoid mode.

The robot in vehicle mode presents a ROV-like configuration which minimizes drag forces, and consequently, the energy required for long-distance displacements through the water (Section 6.4.2). The underwater robot can be remotely operated using a joystick or any master device, as for ROVs. Accordingly, the developed technologies for handling underwater vehicles such as launch and recovery systems (LARS) or tether management systems (TMS), could be conveniently implemented for this transformable robot (see, Figure 3.3).

Transition between modes can be realized in different ways depending on the available propulsion and ballast systems. One possible transition occurs when the

Figure 3.3: LARS and TMS systems, (a) work-class ROV, and (b) atmospheric diving suit. Source: Sperre and OceanWorks, respectively.

robot in vehicle mode lands on the working area, changes from positive to negative buoyancy, and then performs a standing-up motion by using its arms and legs simultaneously to reach an anthropoid configuration (Section 3.5.1). The inverse process can be done to change back from anthropoid to vehicle mode.

Positive buoyancy is important to minimize the energy required for displacements in vehicle mode, while negative buoyancy is desired in anthropoid mode for operating under water without disturbances of buoyancy forces. A similar situation experiences human divers, which have to use weight belts to counteract the buoyancy generated by the diving suit and other equipment.

For a first phase of development, the prototype is intended to have low power propellers and a static ballast system in order to test both functional modes separately. A variable ballast system, proposed as future work in Chapter 8, can be used to perform the mentioned transitions automatically.

3.2.3 Hardware System Overview

Once the design requirements are specified, the detail design process begins. Such process is characterized to require several iterations of virtual prototypes before achieve a first real prototype. The robot design has been realized with a modular approach, obtaining around 25 virtual prototypes along one year of design works. The final CAD model is presented in Figure 3.4, pointing out the modules and sections on which the design of each subsystem is described.

3. Hardware Architecture of an Underwater Anthropoid Robot

Figure 3.4: CAD model of the Underwater Anthropoid Robot (Patent number: ES 2544007 B2 - UPM 2016).

3.3 Design of Robot Head and Torso

Formed by a rigid stainless steel structure, the torso of the robot diver is designed to give support to the head, forelimbs and rear limbs, as well as the underwater control unit. Also, a static ballast system and several propellers are included for displacement in vehicle mode. Figure 3.5 depicts a CAD model of the robot torso, pointing out the main parts and rotational joints.

Nine hydraulic cylinders are included on the torso to actuate different parts of the robot. These actuators have the same parameters as the cylinders selected for arms and legs in Section 3.5, being 25mm bore size and 200mm stroke. Two CHNC25-200 cylinders are placed horizontally to actuate the shoulder joints (S)

3.3 Design of Robot Head and Torso

of the robotic arms, another two are vertically placed side-by-side on the frame to actuate the hip joints (V) corresponding to the robot legs.

Five CHNL25-200 cylinders are arranged parallel to each other on the torso frame. Head motion is performed by the central cylinder on the frame, while the other actuators are used for auxiliary functions. For instance, to actuate the offset wrists or robotic hands, as well as mission related tools or even external systems. For this application, two cylinders are used to actuate the robotic hands (see, Section 3.6.2), while the other two remain uncoupled.

Ballasting and trimming of the underwater robot are performed through adjustable flotation and counterweight systems, which are attached on the back and bottom of the torso frame, respectively. The propulsion is realized by means of eight electric thrusters using a brushless motor to speed up a four-bladed screw propeller according to an input control signal (see, Section 3.3.2).

The robot head gives visual and acoustic feedback to a human operator in both vehicle and anthropoid modes. Thus, tilt motion of the head is instrumental to locate the sensors, when the robot transforms between its functional modes.

Figure 3.5: CAD model of the robot head and torso, (S) shoulder joints, (N) neck joint, and (V) hip joints.

3. Hardware Architecture of an Underwater Anthropoid Robot

Figure 3.6: CAD model of the robot head and components, (a) frontal view, (b) lateral view, where (N) is the neck joint.

The robot head, shown in Figure 3.6, is equipped with a pan-tilt-zoom (PTZ) dome camera, commonly used for security surveillance. To avoid water contact, the PTZ camera is installed inside a transparent pressure-proof hollow cylinder. Security cameras are suitable for taking images in low light conditions, as is usually the case in underwater environments. However, two diving flashlights are installed side-by-side on the head to enhance light conditions when required.

Optionally, a compact imaging sonar (Tritech Micron Sonar) can be strategically mounted on top of head, to be used in vehicle and anthropoid modes for obstacle avoidance and target recognition. Also, a current meter can be fitted on back of head to measure the forces exerted from the water currents. This measurement device, based on a parallel mechanism, can be used in vehicle mode to react to external disturbances *e.g.*, in position keeping maneuvers.

The mechanism designed for tilt motion of the head is treated in the following section. The ballast and propulsion systems are described in Section 3.3.2, and the parallel current meter is described in Section 3.3.3.

3.3.1 Offset Slider-Crank Mechanism

Tilt motion of the robot head is performed through an offset slider-crank mechanism (OSC) composed by a RRRP closed kinematic chain. The elements and design parameters of the planar OSC mechanism are shown in Figure 3.7.

3.3 Design of Robot Head and Torso

The input slider is formed by a hydraulic cylinder attached to the torso frame, whose rod is extended and blocked in rotation (*i.e.*, prismatic joint); on top of the extended rod there is a rotational joint B. The output crank link, included in the head base, presents a rotational joint (N) corresponding to the neck joint and a rotational joint (A) on back of head. Slider and crank are linked by a coupler or connecting rod between (A) and (B) which closes the kinematic chain.

The tubular frame allows to install the head at an adjustable distance a_3 with respect to the slider. Let s be the linkage stroke, a_1 the crank length, a_2 coupler length, and α the head orientation. Construction parameters b and h are defined by the head design as $b=59\text{mm}$ and $h=67.5\text{mm}$, such that

$$a_1 = +\sqrt{b^2 + h^2} = 89.65\text{mm}. \quad (3.1)$$

Translational motion of the slider is limited between $s_1=225\text{mm}$ and $s_2=53\text{mm}$,

Figure 3.7: Schematic view of the OSC mechanism for head motion, (a) transmission elements, (b) design parameters.

3. Hardware Architecture of an Underwater Anthropoid Robot

whose values are defined by physical constraints of the frame and hydraulic cylinder, respectively. Rotational motion of the head must vary between $\alpha = 150^\circ$ when the robot head is fully backward *e.g.*, displacements in vehicle mode, and $\alpha = 30^\circ$ when the head is fully forward *e.g.*, manipulation in anthropoid mode.

From Figure 3.7, the relation between ϕ and α can be expressed as

$$\phi = \frac{3\pi}{2} - \alpha - \text{atan2}(h, b). \quad (3.2)$$

Thus, the OSC mechanism must be designed to transform translational motion of the slider into rotational head motion, according to the following positions:

Table 3.5: Accuracy points of the OSC linkage.

i	α_i	ϕ_i	s_i
1	30°	71.16°	225mm
2	150°	191.16°	53mm

Given the crank length a_1 , the design problem consists in finding the coupler length a_2 , and offset distance a_3 , satisfying the accuracy points listed in Table 3.5. Hence, the algebraic methods developed in (Freudenstein, 2010) can be applied for the dimensional synthesis of the OSC linkage using the displacement equation

$$K_1 s \cos(\phi) + K_2 \sin(\phi) - K_3 = s^2, \quad (3.3)$$

where

$$K_1 = 2a_1, \quad (3.4)$$

$$K_2 = 2a_1 a_3, \quad (3.5)$$

$$K_3 = a_1^2 - a_2^2 + a_3^2. \quad (3.6)$$

Writing (3.3) for the pairs of values (ϕ_1, s_1) and (ϕ_2, s_2) yields the system

$$K_1 s_1 \cos(\phi_1) + K_2 \sin(\phi_1) - K_3 = s_1^2, \quad (3.7)$$

$$K_1 s_2 \cos(\phi_2) + K_2 \sin(\phi_2) - K_3 = s_2^2, \quad (3.8)$$

3.3 Design of Robot Head and Torso

which can be solved for K_2 and K_3 such that

$$K_2 = \frac{s_2^2 - s_1^2 + K_1 [s_1 \cos(\phi_1) - s_2 \cos(\phi_2)]}{\sin(\phi_2) - \sin(\phi_1)}, \quad (3.9)$$

$$K_3 = K_1 s_1 \cos(\phi_1) + K_2 \sin(\phi_1) - s_1^2. \quad (3.10)$$

Hence, the geometric parameters of the OSC mechanism are obtained as

$$a_3 = K_2 / K_1 = 124.5\text{mm}, \quad (3.11)$$

$$a_2 = +\sqrt{a_1^2 + a_3^2 - K_3} = 200\text{mm}. \quad (3.12)$$

3.3.2 Stability and Propulsion

As mentioned earlier, the torso is equipped with a static ballast system composed by floats and weights placed strategically on the torso frame to manually adjust buoyancy and orientation of the underwater robot (see, Figure 3.8).

The flotation system allows to adjust vehicle buoyancy, and consists of n stacked stiff foam boards made in expanded polystyrene (EPS), which can be attached to the torso by means of six rods connected by pairs to a support plate using nuts. Each rod is formed by a threaded rod covered by a plastic hose.

Figure 3.8: Components for ballasting and trimming, (a) adjustable flotation system, (b) adjustable weight system.

For shallow-diving applications, this low-cost system allows to adjust buoyancy forces by adding foam boards as needed. Syntactic foams are used for remotely

3. Hardware Architecture of an Underwater Anthropoid Robot

operated vehicles working at extreme depths, nevertheless is toxic to make and cut, and more expensive than EPS foams (Moore et al., 2010).

Using a similar approach, the adjustable weight system is formed by m weight discs stacked in two columns, which are attached to the torso frame by means of a stainless steel plate. The weight discs are made in cast iron and protected with anti-corrosion coatings. This low-cost system allows to trim for pitch and roll deviations by adding discs as needed. Lead is an ideal material for static ballast systems due to its high density, but it presents some environmental toxicity.

For motion in vehicle mode (Chapter 6), the robot is adjusted to be slightly positively buoyant with an horizontal orientation, using 6 floats* and 16 weight discs of 1kg each, thus, the vehicle will surface under a power failure situation. The robot in anthropoid mode is equipped with 2 floats and 16 weight discs, in order to produce reaction forces for quadrupedal locomotion (Chapter 5).

Figure 3.9: Hi-Flow 400HFS-L thruster.

The underwater robot is fitted with a propulsion system including multiple thrusters driven by brushless motors (Figure 3.9). The thrusters are aligned with the principal axes of motion of the robot in vehicle mode, and must overcome the resistive forces exerted on the vehicle as it moves through the water.

For steady motion thrust and drag forces are in balance, hence, the thrust required can be roughly estimated using the equation (Fossen, 1994),

$$f_D^z = \frac{1}{2} \rho C_D A^z w^2, \quad (3.13)$$

*Each EPS float produces an upward buoyancy force of approximately 160N.

3.3 Design of Robot Head and Torso

Table 3.6: Parameters for drag force estimation.

parameter	ρ	C_D	A^z	w
value	1000kg/m ³	2	0.8m ²	0.5m/s

where ρ denotes the water density, C_D is a dimensionless coefficient, A_z is the frontal area along z axis, and w is the linear velocity along the same axis.

According to (Moore et al., 2010), for a non-streamlined vehicle the drag coefficient C_D can take values greater than 1. For this open frame robot the drag coefficient is assumed to be,

$$C_D = 2, \quad (3.14)$$

with the aim to warrant that propulsion system is well dimensioned. In the same way, the z axis has been chosen for thrust calculation because the vehicle presents maximum frontal area along such direction.

Equation (3.13) is solved for the parameters listed in Table 3.6, obtaining

$$f_D^z = 200\text{N}. \quad (3.15)$$

Thrusters are generally designed to provide maximum thrust at bollard (*i.e.*, in a fixed position). As the vehicle moves under water the thrust decreases around 10% per knot of forward speed (Tecnadyne, 2012). Then, the thrust required when the robot moves at 0.5m/s ($\approx 0.972\text{kn}$) is calculated as

$$f_T = \frac{f_D^z}{0.9^{(0.972)}} = 221.6\text{N}. \quad (3.16)$$

For a relatively low cost compared with similar models, the Hi-Flow 400HFS-L thruster provides a maximum thrust of 67N (datasheets can be downloaded at <http://www.crustcrawler.com/products/urov2/>). Hence, a total of eight thrusters are used to propel the underwater vehicle with 3-DOF.

As can be observed in Figure 3.5, four electric thrusters are installed parallel to the z axis for depth positioning. Another four thrusters are placed parallel to the x axis for heading and forward speed motion. Vehicle motion and the arrangement of eight thrusters is further described in Chapter 6.

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It is worth mentioning that additional drag component of the umbilical cable are not included in this calculation, assuming that the robot prototype works on calm water for a first development phase. For deep-diving applications in open waters, a more powerful propulsion system must be considered using pressure compensated thrusters, as well as the use of tether management systems.

3.3.3 Parallel Current Meter

Along this research, a new device for water current measurement is designed and patented. Based on a parallel mechanism, the speed and direction of water can be measured according to the drag force exerted by the fluid over a spherical element. The parallel current meter can be used as feedback element in a control loop to compensate the external forces exerted by water currents on the robot.

Figure 3.10: CAD model of the parallel current meter
(Patent number: ES 2525394 B2 - UPM 2015).

According to Figure 3.10, the measurement device includes a spherical parallel mechanism formed by a moving base (7) linked to a fixed base (1) through a mast (2) and two kinematic chains (3) formed by universal (4), prismatic (5), and spherical (6) joints. Attached to the moving base (7) a tube (8) supports a hollow spherical canister (9) fitted internally with an inertial measurement unit (10), which registers the spatial orientation of base (7) relative to (1) produced by action of the fluid over the spherical canister (9).

Figure 3.11: Measurement method of the parallel current meter (PM: parallel mechanism, DE: drag equation).

As presented in Figure 3.11, the joint coordinates δ_n of the mechanism are obtained from an inverse kinematic model (IK) using the sphere position $\mathbf{p}$ and moving base attitude q computed by the inertial measurement unit (IMU). Such coordinates are multiplied by the elastic constants k_n of the springs fitted in the parallel mechanism to calculate the corresponding joint forces $\mathbf{f}_n$.

The transposed Jacobian J^T is used to map the joint forces into the drag force $\mathbf{f}_d$ exerted on the sphere. Using the sphere radius r_s , the water speed v_w , and direction $\hat{\mathbf{v}}_w$ are derived from the drag equation (Newman, 1977). The IK model and Jacobian of the parallel mechanism are treated in (Serracín et al., 2012).

In a first development phase, the robot prototype is tested on calm waters, thus, the development of a current meter prototype is left as future work (see, Chapter 8). Hence, the robot head is fitted with camera and imaging sonar.

3.4 Design of an Underwater Control Unit

The underwater control unit (UCU) is defined as a sub-system containing all the components for signal processing and control of the underwater robot.

Such components remain inside an aluminium vessel to avoid water contact, and are installed on a frame attached to a rigid flange plate, which is fitted with electrical and hydraulic connectors to link sensors and actuators of the robot. Figure 3.12 shows the control unit and points out the main components.

The umbilical cable provides power and data to the control unit, which contains a real-time controller (NI CompactRIO), two hydraulic manifolds fitted with 24 servovalves, signal conditioning circuits, and navigational sensors *i.e.*, inertial

3. Hardware Architecture of an Underwater Anthropoid Robot

Figure 3.12: CAD model of the underwater control unit, (a) sectional view of the aluminium vessel and internal components, and (b) controller, hydraulic elements and electronic boards (EUC: electrical underwater connector, P: pressure port, T: tank port).

measurement unit (IMU) and depth sensor. Hydraulic pressure is provided by a variable volume piston pump Parker PVP23 driven by a 15kW engine.

Spatial orientation of the robot is measured by a 9DOF Razor IMU* formed by three accelerometers, three gyroscopes and three magnetometers. The output of all sensors are filtered and processed by an on-board ATmega328. IMU readings provide attitude measurements which are used for heading control in Chapter 6. Further details of the measurement algorithm are given in Section 6.3.1.

Depth measurements are performed using a pressure transducer PAA-21[†], consisting on a piezoresistive pressure sensor mounted in an oil filled capsule. The media pressure is isolated by a stainless steel diaphragm and transferred to the pressure sensor through the oil. Pressure readings are converted to depth measurements and used for depth control in Chapter 6.

*<https://www.sparkfun.com/products/10736>

[†]<http://www.keller-holland.nl/pdf/Serie21-e.pdf>

3.4 Design of an Underwater Control Unit

The embedded controller receives data from the robot sensors and sends commands to the thrusters and servovalves to control robot movements. Hydraulic servovalves and manifolds are described in Section 3.4.1. Controller and signal processing circuits are presented in Section 3.4.2. The design of electrical connectors for underwater operation is treated in Section 3.4.3.

3.4.1 Servovalves and Hydraulic Manifolds

The hydraulic actuators of the anthropoid robot are controlled using electrohydraulic servovalves. Flow control servovalves are well suited for closed-loop position control as they present a smooth flow-signal curve due to zero lap or little underlap on all orifices *i.e.*, no mechanical deadband (Jelali and Kroll, 2003). Figure 3.13 presents the servovalve used in the underwater control unit.

Figure 3.13: Two-stage flapper-nozzle servovalve, (a) Huatong HT-803/10 electro-hydraulic servovalve, and (b) internal components and operating principle. Source: Moog, Inc.

As can be observed in Figure 3.13.b., an electrical current is applied to the torque motor coils producing a magnetic force. This causes the armature and flapper to rotate about the flexure sleeve and divert fluid flow to one spool end.

Movement of the spool connects the pressure port (P) to one control port and the tank port (T) to the other control port. The spool displacement is also applied to one end of the feedback spring, creating a restoring torque on the armature.

3. Hardware Architecture of an Underwater Anthropoid Robot

Figure 3.14: Hydraulic manifold, (a) CAD model of the manifold fitted with servovalves (b) sectional views of the manifold plate. The manifold design is scalable to any number of servovalves. For this application, manifolds are fabricated for 12 servovalves each.

Restoring torque increases until the spool achieves an equilibrium position where feedback torque equals torque due to input current. Thus, for a constant valve pressure drop, the output flow is proportional to spool position, which is proportional to input current. Further details are given in (Moog, 2015).

The servovalves are provided by Huatong Hydraulic Pneumatic Manufacturing (<http://huatong.en.china.cn/>). HT-803/10 model, shown in Figure 3.13.a., has a rated pressure of 7MPa, a rated flow of 10L/min, and provides a frequency response of approximately 100Hz, which is sufficient for low speed motion in a high density environment, considering the actuators selected in Section 3.5.

Servovalves are high performance components, but they are very sensitive to fluid contamination, thus, a filter (5μ absolute) is installed on the displacement pump which supplies hydraulic fluid to the UCU through the umbilical cable.

The underwater control unit is fitted with 24 servovalves connected in parallel and distributed in two hydraulic manifolds. The design of hydraulic manifolds reduces the volume necessary to contain a large number of servovalves, reducing leak risks and the number of hydraulic fittings required (Figure 3.14.a.).

3.4 Design of an Underwater Control Unit

Hydraulic manifolds are fabricated from aluminium alloy blocks in a vertical machining center, to precisely locate the hydraulic ports of each servovalve. The threaded holes are used to fix the servovalves on the manifold block using allen head fasteners, and to attach the assembly on the UCU frame.

As can be observed in Figure 3.14.b., the hydraulic ports (P) and (T) for each servovalve are connected by means of horizontal passages with two longitudinal pressure and tank ports. Once the manifold is fabricated, the auxiliary holes are sealed using set screws and thread sealant (Parker GT-21). A cleaning process is performed on the machined parts before installing the servovalves.

3.4.2 Controller and Signal Conditioning

CompactRIO controller is used to manage the sensors and actuators of the underwater robot. CompactRIO (cRIO) is a reconfigurable embedded system made by National Instruments for industrial control applications. It includes a processor running a real-time operating system (RTOS), a reconfigurable field-programmable gate array (FPGA), and interchangeable I/O modules (Figure 3.15).

The cRIO-9022 controller features an industrial 533 MHz Freescale MPC8347 real-time processor and contains 256 MB of DDR2 RAM and 2 GB of nonvolatile storage for holding programs (NI, 2014). The controller provides two Ethernet ports for network communication, and connects to cRIO-9114 reconfigurable 8-slot chassis, fitted with a Virtex-5 LX50 FPGA produced by Xilinx.

Figure 3.15: CompactRIO controller (a) and FPGA chassis with eight I/O modules (b). Source: National Instruments.

3. Hardware Architecture of an Underwater Anthropoid Robot

Table 3.7: CompactRIO modules and robot components.

slot	module	description	component	qty.
1	NI 9871	RS485 serial ports	camera, IMU	1, 1
2	NI 9403	32-Ch DIO, 5V TTL	abs. encoder	12
3	NI 9264	16-Ch AO, $\pm 10V$	servovalve	12
4	NI 9264	16-Ch AO, $\pm 10V$	servovalve	12
5	NI 9403	32-Ch DIO, 5V TTL	abs. encoder	12
6	NI 9401	8-Ch DIO, 5V TTL	thruster	8
7	NI 9201	8-Ch AI, $\pm 10V$	pressure sensor	1
8	NI 9977	slot filler module	IMU board	1

DIO: digital input output / AO: analog output / AI: analog input

The I/O modules allow to connect sensors and actuators to the embedded controller. The module NI 9871 has four port for serial data communication, one of them is used to send commands to the PTZ dome camera, while another port is used to read the orientation data provided by the IMU. Two digital I/O modules NI 9403 are used to receive the encoder position. Another digital I/O module NI 9201 is used to send PWM control signals to the electric thrusters.

Two analog output modules NI 9264 are used to output a voltage signal to the flow control servovalves. An analog input module NI 9201 is used for the pressure sensor readings. A slot filler module NI 9977 is adapted to house a 9DOF Razor IMU with a fixed orientation inside the control unit (see, Table 3.7).

Figure 3.16: SSI master interface, (i) pins for module NI 9403, (j) pins for encoder EMA22 ($R1=R2=120\Omega$).

3.4 Design of an Underwater Control Unit

Figure 3.17: Buffer amplifier and voltage to current converter (i) from module NI 9264, (j) to servovalve HT-803/10 ($R_1=250\Omega$).

The robot joints are measured by magnetic absolute encoders Eltra EMA22* with 2048 pulses per revolution of resolution and synchronous serial interface (SSI) output. SSI interface transmits the absolute encoder position by a serial data line synchronized by a clock signal. The SSI signals are transmitted differentially (RS422) to avoid interferences in longer transmission distances.

As shown in Figure 3.16, the SSI master interface is formed by an RS422 transceiver MAX3087†, used to generate the differential signals from/to digital I/O ports. MAX3087 is a high-speed transceiver for RS485/RS422 communication containing one driver and one receiver (full-duplex communication).

The coils of servovalve HT-803/10 are connected in parallel and can be commanded by a $\pm 40\text{mA}$ current signal. As depicted in Figure 3.17, the first circuit stage is formed by a voltage buffer using an operational amplifier OPA552. Another OPA552 is used to convert the $\pm 10\text{V}$ voltage signal of the cRIO module (NI 9264) into a current signal of $\pm 40\text{mA}$ for the servovalve. Such op amps have high-current (200mA) capability being suitable for servo applications‡.

A low amplitude and high frequency periodic signal, named dither, is sometimes superimposed on the servovalve input to avoid spool striction and improve system resolution. Dither signal can be used for pressure and velocity control loops, but is rarely needed in a position loop (Moog, 2015). Dither should be kept to a minimum to not compromise servovalve life.

*<http://www.eltra.it/products-eltra-encoder-for-motion-control/>

†<http://datasheets.maximintegrated.com/en/ds/MAX3080-MAX3089.pdf>

‡<http://www.ti.com/lit/ds/symlink/opa552.pdf>

3. Hardware Architecture of an Underwater Anthropoid Robot

3.4.3 Electrical Underwater Connectors

Despite an extensive variety of electrical connectors for marine applications, the available models are expensive and bulky for a high number of pins. The restricted dimensions of the underwater control unit requires a high number of waterproof connections in a reduced area. Thus, a customized electrical underwater connector (EUC) is designed and tested in shallow waters. The CAD model and functioning details of the EUC prototype are shown in Figure 3.18.

Figure 3.18: Sectional view of the underwater electric connector based on hydraulic JIC fittings.

The underwater connector uses hydraulic JIC fittings (SAE J514.37°) to keep the internal components dry and sealed from the external environment. The seal is produced by physical contact between cone-shaped surfaces of the crimp and bulkhead fittings, which are prepared to support considerable pressures.

Inside the hydraulic fittings, 37 pin sockets are mounted on a circular printed circuit board (PCB) within a plastic coupling, and 37 male pins are arranged inside another coupling. The plastic parts are 3D printed in ABS, and designed with a specific form to prevent mismating of connectors.

Electrical power supply as well as control data are provided to the underwater control unit using eight EUC (Figure 3.12). Each waterproof connector can be adapted for low or high power cables by grouping pins directly on the board.

The design and development of EUC constitutes a technological challenge, because a high number of small parts must be correctly assembled to allow reliable electrical connections, and keep system modularity.

3.5 Design of Hydraulic Arms and Legs

According to the design requirements, stated in Section 3.2, the robotic diver presents two forelimbs and two rear limbs whose geometric parameters are inspired on the proportions of primates. Figures 3.19 and 3.20 show a CAD model view of the robot limbs pointing out the rotational joints and main parts.

Figure 3.19: CAD model of the robot arm. (S) and (R) are the shoulder joints, (E) elbow, (C), (W) and (T) are the wrist joints.

The robot arm has 6-DOF (see, Table 3.4) and is formed by two segments, being the upper arm and the forearm (robotic hands are treated in Section 3.6). The robot arm is made in high density polypropylene, aluminium, bronze and stainless steel; smaller parts are fabricated in ABS plastic.

The upper arm contains three rotational joints, shoulder joint (S) is actuated from the robot torso, and the rest by two opposite inverted slider-crank mechanisms (ISC), one for the shoulder joint (R) and another for the elbow joint (E). Both ISC linkages have a common connecting link which is the upper link.

The robot wrist is formed by two passive rotational joints and one hydraulic twisting mechanism. The passive joints are configured as two perpendicular rotational joints (C) and (W) with a locking mechanism, used to orientate and fix the

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end-effector of the robotic arm. The twisting joint is actuated by a hydraulic orbital motor with a parallel axis mechanism for position control; the main function of this subsystem is to rotate the hands or any tool used by the robot. Further details of the robot wrist are given in Section 3.5.5.

Figure 3.20: CAD model of the robot leg. (V) and (H) are the hip joints, (K) knee joint, and (A) ankle joint.

Each robotic leg has 4-DOF (see, Table 3.4) and comprises four links, as depicted in Figure 3.20. The rear limbs are made in stainless steel, bronze, and polypropylene, small parts are manufactured in aluminium and ABS plastic.

The rotational hip joint (V) is actuated from the robot torso. The thigh link is similar to the upper link of the arm, hence, rotational hip joint (H) and knee joint (K) are provided by two opposite ISC mechanisms sharing a common connecting link. The calf link and rotational ankle joint (A) are part of a single ISC linkage which orientates the foot along the sagittal plane of the robot.

For this application, a first approach of the foot design is implemented, being a rigid foot for supporting the robot during quadrupedal locomotion. Nevertheless, an interesting approach could be to adapt the design of the robotic hands and develop a robotic foot not only for walking, but also for climbing and fixing on

3.5 Design of Hydraulic Arms and Legs

submerged structures and also perform manipulation tasks *e.g.*, to handle tools or structural elements. Thus, the development of ape-like feet with gripping and manipulation capacities is left for future versions of the prototype.

The ISC mechanisms of the robot arms and legs are driven by linear hydraulic actuators provided by SMC Corporation, due to their high power-to-weight ratios, waterproof design, and water resistant materials. Hydraulic cylinders of Series CHN includes double acting actuators with stainless steel piston rod and bore size of 20mm and 25mm for an operating pressure of 7MPa, developing a theoretical output force of 2198N and 3430N, respectively. Datasheet can be downloaded at <http://content2.smcetech.com/pdf/chn.pdf>.

The remainder of this section studies the standing-up motion of the robot for optimal linkage design and actuator selection, describes the design of the rotational joints for underwater operation, and presents the robot wrist.

3.5.1 Simulation of the Standing-up Motion

As presented in Section 3.2.2, standing-up motion occurs when the underwater robot transforms from a vehicle mode into an anthropoid mode, deploying its arms and legs through a coordinated motion sequence (see, Figure 3.21).

When immersed, the effective weight of the robot is significantly reduced by the buoyancy forces. For slow speed motion, buoyant forces are dominant over hydrodynamic forces, and a reduced-gravity model of the robot can be used to predict the forces required for an equivalent motion under water. Similar approaches are applied for locomotion studies in (Newman, 1992) and (Martinez et al., 1998).

Figure 3.21: Snapshot sequence for the standing-up motion using multibody simulation software MSC Adams.

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Table 3.8: Robot parameters for dynamic simulation.

link	foot	calf	thigh	torso	upper	forearm
length (mm)	300	500	500	900	500	745
weight in water (N)	29.4	29.4	29.4	1078	29.4	98

joint	A	K	H	R	E
initial angle (deg)	36	12.4	0	36	82.3
final angle (deg)	65	66.4	25	43.7	130

The forces involved in the standing-up motion are of particular interest to design the actuation mechanisms of the robot limbs through a dynamic simulation of a simplified robot model. The parameters listed in Table 3.8 are used into dynamic simulation package MSC Adams to calculate the required torque profiles for each rotational joint involved in the standing-up movements.

For the simulation, it is assumed that the underwater robot moves at slow speed with negative buoyancy, the robot torso is at 30° with respect to the ground during the motion, and that exists slippage of feet and hands with respect to the ground. To account for payload and friction, the effective weight of the torso is

Figure 3.22: Joint torque profiles for the standing-up motion, (a) torque applied on the rear limb, and (b) torque on the forelimb.

3.5 Design of Hydraulic Arms and Legs

considered as twice its value. By this way, the results will tend to over-dimension the actuators, which is a desired choice for a first prototype.

As observed in Figure 3.22, the rear limbs of the robot develop higher torques than the forelimbs due to the torso orientation. Higher torque values are found at the beginning of the motion where ankle joint (A) exerts a torque of 295Nm, and hip joint (H) develops 293Nm. As the robot continues the movement, all the joint torques decreases from the initial values in a nonlinear fashion.

According to these results, the parameter ($\tau_{max} = 300Nm$) is adopted as a threshold for hydraulic actuator selection. In Chapter 7 the robot prototype is tested under water, and validation experiments of the standing-up motion are performed to verify the calculations carried out in the design phase.

3.5.2 Inverted Slider-Crank Mechanism

The arms and legs of the robot are based on the inverted slider-crank (ISC) mechanism, formed by a RRPR closed kinematic chain. The ISC linkage is an inverted configuration of the slider-crank mechanism. In this form, the prismatic joint can be a linear actuator that drives the rotation of the crank.

As introduced in Section 3.5, a hydraulic cylinder of Series CHN can be used to actuate the linkage (CHNC model). Figure 3.23 represents the ISC mechanism and defines the design parameters used on this analysis.

Figure 3.23: Schematic view of the ISC mechanism and geometric parameters ($d = 500mm$, $x_4 = 30mm$).

3. Hardware Architecture of an Underwater Anthropoid Robot

The joint angle θ can be expressed as follows

$$\theta = \gamma - \alpha_1 + \alpha_2, \quad (3.17)$$

$$\alpha_1 = \arctan(x_2/x_1), \quad \alpha_2 = \arctan(x_4/x_3). \quad (3.18)$$

Equation (3.17) results in an angle equal to zero when the cylinder is fully retracted *i.e.*, vertical upper link, and 90° when the actuator is extended *i.e.*, horizontal link. The law of cosines gives the following expression

$$x^2 = \underbrace{(x_1^2 + x_2^2)}_{x_{12}^2} + \underbrace{(x_3^2 + x_4^2)}_{x_{34}^2} - 2 x_{12} x_{34} \cos(\gamma). \quad (3.19)$$

Angle γ is extracted from (3.17) and inserted into (3.19) to obtain a definition of the cylinder extension $x \in \mathbb{R}$ as a function of the joint angle θ , such that

$$x = \sqrt{x_{12}^2 + x_{34}^2 - 2 x_{12} x_{34} \cos(\theta + \alpha_1 - \alpha_2)}. \quad (3.20)$$

Angle β can be extracted from the law of cosines, expressed as

$$x_{12}^2 = x^2 + x_{34}^2 - 2 x x_{34} \cos(\beta). \quad (3.21)$$

The lever arm $\ell \in \mathbb{R}$ is defined as the shortest distance from the cylinder line of action to the rotation axis of the joint. Once x and β are known, the lever arm can be obtained by applying the law of sines, hence*

$$\ell = x_{34} \sin \left[\arccos \left(\frac{x^2 - x_{12}^2 + x_{34}^2}{2 x x_{34}} \right) \right]. \quad (3.22)$$

Finally, the joint torque τ can be calculated as

$$\tau = F \ell(\theta, x_1, x_2, x_3), \quad (3.23)$$

where F is the cylinder force. Equation (3.23) is a nonlinear multivariable function depending on the joint angle θ and the design parameters x_1 , x_2 , and x_3 (parameter

*The results from $\arccos$ were verified for all the possible values inside the joint range.

x_4 is considered as a constant equal to 30mm). For a constant input force, the higher the value of the lever arm, the higher the torque generated by the joint.

3.5.3 Optimization of the ISC Mechanism

The aim is to calculate optimal values for the design parameters of the ISC mechanism that maximize the joint torque, and satisfy a set of constraints introduced by the designer. In this sense, the negative of Equation (3.23) is used as the objective function of a constrained optimization problem. The Matlab function *fmincon* is used to find the maximum joint torque subject to the following constraints

$$250 \leq x_1 \leq 500, \quad 50 \leq x_2 \leq 500, \quad 0 \leq x_3 \leq 500, \quad (3.24)$$

$$x(\theta = 90^\circ) - 2x(\theta = 0^\circ) + x_{min} \leq 0, \quad (3.25)$$

$$\ell(\theta = 90^\circ) - \ell(\theta = 0^\circ) \leq 0. \quad (3.26)$$

The lower and upper bounds of the design variables are given in millimetres by constraint (3.24). Upper bounds are limited to the maximum link length $d = 500mm$, defined by the anthropoid proportions on Section 3.2.1.

Figure 3.24: Torque profile of the ISC mechanism from 0° to 90° for different cylinder strokes, (a) 25mm bore size, and (b) 20mm bore size. The plane represents parameter τ_{max} obtained in Section 3.5.1.

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Table 3.9: Optimized design parameters – ISC mechanism.

parameter	initial estimate		optimized value		selected value	
	(i)	(j)	(i)	(j)	(i)	(j)
x_1 (mm)	50	40	111.8	104.1	110	105
x_2 (mm)	50	40	83.2	52.1	85	40
x_3 (mm)	250	400	475.0	475.0	475	475
stroke (mm)	100	80	197.1	201.6	200	200

(i): joint range 0° to 90° / (j): joint range 0° to 120°

Equation (3.25) is a nonlinear inequality constraint that restricts the difference of the cylinder extension between the fully extended position, and the fully retracted position to fit with the minimum retracted length of a conventional single-stage actuator. According to the manufacturer datasheet, parameter x_{min} is a constant equal to 170mm for the hydraulic cylinders of CHN Series.

The constraint expressed in (3.26) restricts the optimal mechanism to have more or equal torque for retracted positions than for extended positions, which is a desirable feature considering the torque requirements of Figure 3.22.

Different input values of x_1 are given to the fmincon function ranging from 250mm to 500mm, which is the maximum link length. The obtained output values for x_2 and x_3 satisfying the constraints are stored in memory. As shown in Figure 3.22, the superposition of joint torque profiles for each computed mechanism forms a 3D surface depending on the cylinder stroke and joint range.

According to the obtained results, the selected actuator must have a bore size of 25mm and approximately 200mm stroke to provide the necessary joint torque along all the joint range of the ISC mechanism. For the same stroke, the hydraulic cylinders with 20mm bore size do not satisfy the torque required to perform the standing-up movement and are therefore discarded.

Some of the ISC mechanisms of the robot are required to have a joint range from 0° to 120° (*i.e.*, elbow, knee, and ankle joints). Thus, a similar optimization process is carried out for these joints. The optimized and selected values for each parameter are summarized in the Table 3.9.

3.5.4 Rotational Underwater Joints

Revolute joints allow rotation motion to an output link with respect to an input link around a rotation axis. According to (Kandray and Kroll, 2010), revolute joints can receive different names depending on the orientation of their axes.

For a rotational joint, the rotation axis is perpendicular to the axis of the links. In a twisting joint the axis is parallel to both links, while a revolving joint presents a rotation axis parallel to one link and perpendicular to the other.

The underwater anthropoid robot developed in this research implements rotational joints for almost all its axes, and presents two twisting joints at the forelimbs charged to rotate the end effectors (described in Section 3.5.5).

As the robotic arms and legs are intended to work in underwater conditions, particular considerations have to be taken for materials and joint design.

Figure 3.25 depicts a rotational joint of the robot arm designed for underwater operation, pointing out its main elements. It is worth mentioning that the working principle of this joint applies for all the rotational joints of the robot.

Figure 3.25: Sectional view of the rotational joint (W).

The output link rotates relative to the input link around a stepped stainless steel shaft, which is supported by two bronze alloy bushings fixed on the input link by four countersunk screws each. Rotational motion is transmitted from the output link to the pulley by means of a pin connecting both parts, then, the pulley transmits the motion to the shaft through a feather key.

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The shaft of the joint have a female thread to fix a disk using a screw and stop the shaft in one axial direction. The other end presents a male thread for an auto blocked nut which is screwed on the shaft end, allowing to adjust the axial backlash of the joint. After the nut is screwed down, a small magnet is fixed to the end of the shaft, and a magnetic absolute encoder is positioned on the bronze bushing which is concentric to the axis of rotation.

Once the output link rotates, shaft and magnet rotate in the same way and such rotation is measured by the encoder which is fixed on the input link. Additionally, rotational joints (C) and (W) can be locked using an extra pin (not shown in the figure), placed between the input link and the pulley; the holes in the pulley are used for different locking positions.

3.5.5 Orthogonal Offset Wrist

For a robot manipulator, any mechanism with three intersecting axes of rotation is known as a spherical wrist (Pieper, 1968). In the case of this underwater robot, the forearm presents an offset wrist formed by three revolute joints where only two axes intersect, as observed in the CAD model of Figure 3.26.

Offset wrists are encountered in most hydraulic manipulators used in subsea applications, such as Schilling TITAN 4 or Kraft RAPTOR, and can also be found in some anthropomorphic industrial robots as Fanuc M-710iC/50E and Universal Robots UR10. For bulky actuators, the kinematics of an offset wrist allows easier mechanical design than spherical wrists while the range of collision-free motions of the end-effector is increased (Duchemin et al., 2000).

The forearm wrist contains a twisting joint (T), and two rotational joints (C) and (W) which can be actuated by a cable driven system or can be locked at any convenient angle (*i.e.*, passive joints). Also, joint (W) can be installed at different angles with respect to (C) by means of two bolted flanges, which allows to assemble the forearm in a redundant parallel-axis fashion or even a non-perpendicular configuration. Along this research, (C) and (W) are considered as passive joints and the offset wrist is used in orthogonal configuration.

The shafts of the wrist are coupled to an absolute encoder each for position control. Because the hydraulic motor has no place to install an encoder directly

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Figure 3.26: Components of the orthogonal offset wrist (some parts are removed to show functional aspects).

coupled to its shaft, two pairs of gears are used to transmit the rotary motion from the actuator to the encoder through a parallel auxiliary shaft. Each pair of gears presents an opposite gear ratio, hence, the overall ratio is 1 : 1 such that the encoder take a direct measure of the motor shaft rotation.

The twisting joint motor is an orbital hydraulic motor BMM40, provided by Ningbo Associated Hydraulic Control Technology (<http://www.ashydraulic.com.cn/>). The motor is based on a gerotor mechanism, comprising an internal gear with n teeth which rotates relative to a fixed external gear with $n + 1$ teeth by action of the hydraulic fluid provided by the servovalves.

Finally, the robotic hand connects to the output flange of the wrist and rotates by means of the hydraulic orbital motor. Additionally, the twisting joint is equipped with a diving LED flashlight to illuminate the working area of the hand for any configuration of the underwater anthropoid robot.

3.6 Design of Anthropomorphic Hands

Despite of important advances on the development of dexterous robotic hands, their implementation in real-world applications is not yet satisfactory and is still an open challenge in robotics (Bicchi, 2000).

3. Hardware Architecture of an Underwater Anthropoid Robot

Artificial hands can be classified in two general categories, as anthropomorphic and special-purpose hands. Anthropomorphic hands are designed to mimic the human anatomy and physiology *e.g.*, (Jacobsen et al., 1986), (Shadow, 2013). They usually present a complex kinematic structure and tendon-driven mechanisms using several actuators in order to achieve maximum dexterity.

Special-purpose hands are commonly used for grasping applications in structured environments *e.g.*, (Townsend, 2000), (Robotiq, 2015). A cost-effectiveness design using a minimum number of fingers and actuators is a common feature. Thus, the use of single function end-effectors such as parallel jaws grippers is widely extended for underwater manipulators as in (Kraft, 2005).

Figure 3.27: CAD model views of the right hand, where (i) index finger, (m) middle finger, (r) ring finger, and (l) little finger.

According to the requirements on Section 3.2, the robot hands are not only for grasping objects of different size, but also to support the robot during quadrupedal locomotion (Chapter 5). As the hands will be in permanent contact with water, they must be prepared for underwater operation. For this prototype, a trade-off between anthropomorphism and grasping robustness has to be found.

Hence, the underwater robot is provided with two anthropomorphic hands formed by four mechanical fingers and a thumb installed opposite to them, as represented in Figure 3.27. The hand design is inspired by the work in (SLSA, 2011) consisting on a mechanical linkage similar to a prosthetic hand, placed on the human arm and directly controlled through a set of links connecting the user fingertips with the mechanical fingers of the hand.

3.6 Design of Anthropomorphic Hands

The arrangement and dimensions of the fingers have been adapted to improve grasping conditions, as observed in Figure 3.28. Several modifications have been introduced to allow hydraulic actuation, as well as facilitate fabrication and assembly of the robotic hand. Most of the parts are made in stainless steel, while some small parts are fabricated in aluminium and ABS plastic.

Figure 3.28: Grasp modes of the robotic hand, (a) large diameter power grasp, (b) precision grasp, and (c) circular power grasp.

The robotic hand has up to 5-DOF *i.e.*, one actuator at each finger. Nevertheless, other arrangements requiring less number of hydraulic actuators can also be configured by mechanically coupling the fingers. For instance, the hand can be assembled with 3-DOF using one actuator for the thumb, another for index and middle fingers, and a third actuator for ring and little fingers.

For the purpose of this research, the robotic hand is configured for power grasping using a single actuator. In such configuration, the thumb is fixed in a convenient orientation while the four fingers are coupled using a connecting bar, being simultaneously actuated by one hydraulic cylinder. The robotic hands must be completely closed during quadrupedal locomotion in Chapter 5, but can be instrumental in climbing or manipulation tasks.

3.6.1 Crossed Four-Bar Mechanism

The fingers of the robotic hand are based on the crossed four-bar mechanism (CFB), and the thumb is formed by two CFB mechanisms one after the other having certain links in common. Figure 3.29 represents a side view of one finger and points out its main elements and geometrical parameters.

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CFB linkages have a changeable instantaneous center of rotation (ICR), which is located at the intersection of crank and rocker links. Such polycentric mechanisms can be found in robotics applications, such as the knee joints of a humanoid robot (Hamon and Aoustin, 2010), and a quadruped robot (Khan et al., 2015).

Figure 3.29: Crossed four-bar mechanism and kinematic parameters.

Link dimensions are empirically defined by testing different CAD models of a finger, and selecting lengths that ensure a wide open hand (*i.e.*, $\phi_{open} < 60^\circ$) with no physical interference when the finger is fully closed.

The fingers are arranged parallel to each other, avoiding physical interference between two adjacent fingers. Crank and rocker links are the same for every finger, while the coupler link presents a particular length and δ angle for each finger, to give a more natural appearance to the anthropomorphic hand. The selected parameters are listed in the following table:

Table 3.10: Design parameters of the robotic hand.

length	l_{12}	l_{23}	l_{24}	l_{27}	l_{35}	l_{45}	l_{74}	l_{76}
(mm)	48	12	54	12	54	12	48	40

angle	ϕ_{open}	ϕ_{close}
(deg)	≈ 45	≈ 220

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Figure 3.29 is used to study the relation between coupler and crank *i.e.*, $\phi = f(\alpha)$, which is related to the required stroke for a cable-driven actuation system. Such relation is used to verify that the selected length parameters satisfy the angle parameters ϕ_{open} and ϕ_{close} . The angle ϕ of the coupler link can be expressed as

$$\phi = \pi - \alpha + \omega_3 - \underbrace{(\varepsilon - \varepsilon_1 - \omega_2)}_{\varepsilon_2}. \quad (3.27)$$

The internal angles of $\Delta 247$ are calculated as

$$\omega_1 = \arccos \left(\frac{l_{27}^2 + l_{24}^2 - l_{74}^2}{2 l_{27} l_{24}} \right), \quad (3.28)$$

$$\omega_2 = \operatorname{atan2} \left[\frac{l_{27}}{l_{74}} \sin(\omega_1), \frac{l_{24}^2 + l_{74}^2 - l_{27}^2}{2 l_{27} l_{74}} \right], \quad (3.29)$$

$$\omega_3 = \pi - (\omega_1 + \omega_2). \quad (3.30)$$

Equation (3.30) is inserted into (3.27) to obtain

$$\phi = 2\pi - (\alpha + \varepsilon + \omega_1) + \varepsilon_1, \quad (3.31)$$

where

$$\varepsilon = \arccos \left(\frac{l_{34}^2 + l_{45}^2 - l_{35}^2}{2 l_{34} l_{45}} \right), \quad (3.32)$$

$$\varepsilon_1 = \operatorname{atan2} \left[\frac{l_{23}}{l_{34}} \sin(\pi - \alpha - \omega_1), \frac{l_{34}^2 + l_{24}^2 - l_{23}^2}{2 l_{34} l_{24}} \right], \quad (3.33)$$

$$l_{34}^2 = l_{24}^2 + l_{23}^2 - 2 l_{24} l_{23} \cos(\pi - \alpha - \omega_1). \quad (3.34)$$

Equation (3.31) represents a nonlinear relation between ϕ and α , which can be numerically solved for different values of α to graphically obtain the crank orientation corresponding to ϕ_{open} and ϕ_{close} (see, Figure 3.30). The obtained values are used to calculate the stroke required to actuate the hand fingers.

From Figure 3.29, distance l_{16} can be expressed as follows

$$l_{16}(\alpha) = +\sqrt{l_{12}^2 + l_{26}^2 - 2 l_{12} l_{26} \cos(\alpha + \omega)}, \quad (3.35)$$

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Figure 3.30: Nonlinear relation between coupler and crank angles for a hand finger ($\alpha_{open} = 28^\circ$ and $\alpha_{close} = 108^\circ$).

$$l_{26} = +\sqrt{l_{76}^2 + l_{27}^2 - 2 l_{76} l_{27} \cos(\omega_3)}, \quad (3.36)$$

$$\omega = \text{atan2} \left[\frac{l_{76}}{l_{26}} \sin(\omega_3), \frac{l_{27}^2 + l_{26}^2 - l_{76}^2}{2 l_{27} l_{26}} \right]. \quad (3.37)$$

Finally, the required stroke is calculated as the difference between $l_{16}(\alpha_{open})$ and $l_{16}(\alpha_{close})$. Applying the parameters of Table 3.10, yields

$$l_{16}(\alpha_{open}) - l_{16}(\alpha_{close}) = 32\text{mm}. \quad (3.38)$$

3.6.2 Bowden Cable Actuation

The robotic hand is actuated using a Bowden cable, which is a mechanical control cable used to transmit force by the linear movement of an inner cable with respect to a hollow flexible sheath. It is widely used in bike brake systems, but can also be found on aircraft and exoskeletons *e.g.*, (Goiriena et al., 2009).

The use of Bowden cables is well suited for space-constrained environments, as is the case in the robot hands, allowing remote actuation of the fingers.

Additionally, these control cables allow flexibility since the sheath is clamped at both ends and apply a reaction force which isolates the system, thus, the routing path can be freely changed. The main disadvantage is the low efficiency due to the high friction between cable and sheath (Chen et al., 2014).

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The actuation device shown in Figure 3.31, is used to transmit mechanical force from the hydraulic cylinders located on the robot torso (Section 3.3) to the hands for open-close actuation.

Figure 3.31: Bowden cable actuation system.

The cylinder rod is extended, to pass through the sheet metal frame corresponding to the robot torso. A metal plate and a cable holder are fixed at the rod end. The plate limits axial displacement of the rod between the frame and the mechanical stop, whose longitudinal distance allows a 32mm stroke (3.38).

As the cylinder retracts, the cable moves with respect to the sheath, closing the hand fingers. To open the hand, the actuator extends to release the cable which is collected by action of tension springs installed on the fingers.

For a Bowden cable, the relation between the input force F_{in} exerted on the cable relative to the output force F_{out} at the end of the cable can be expressed through the capstan formula (Carlson et al., 1995)

$$F_{in} = F_{out} e^{(\mu\rho)}, \quad (3.39)$$

where μ is the kinetic friction coefficient and ρ is the total wrapping angle measured in radians. As a rough calculation, the input force of 3430N exerted by the hydraulic actuator of the torso is reduced in the worst case (*i.e.*, stainless steel cable with PTFE sheath $\mu = 0.27$, and fully retracted arm $\rho = 2\pi$) to 629N, which is acceptable for power grasping, as shown in Chapter 7.

3.7 Control Unit Prototype

The correct operation of the underwater control unit (UCU), presented in Section 3.4, is instrumental for a correct performance of the underwater robot, since all acquisition and control functions are realized in this subsystem. Mechanical, hydraulic, and electronic elements are integrated in parallel, considering the system as a whole, and respecting space constraints imposed by the robot.

As can be observed in Figure 3.32, the control unit includes an embedded real-time controller, 24 mechanical feedback servovalves, and 4 electronic boards for signal conditioning. Such components are housed inside an aluminium vessel of $270 \times 320 \times 600\text{mm}$, to protect them of water contact.

Figure 3.32: Underwater control unit components, (a) mechanical structure and hose connections, (b) servovalves and manifold, (c) controller and electronic boards, (d) flange plate and hydraulic fittings, and (e) control unit prototype. Total mass: 28kg.

3.7 Control Unit Prototype

Before installing the servovalves, hydraulic manifolds must undergo a cleaning process that consists on circulating hydraulic oil inside all the plate channels, at operating pressure. The fluid drags any metal particles produced in the machining process, which are then eliminated by the hydraulic pump filter.

For this purpose, several aluminium plates are fabricated to connect the tank and pressure ports with the control ports, ensuring that the oil flows through all the hydraulic channels (see, Figure 3.33). The cleaning process is realized in four cycles of eight hours each, at a pressure of 7MPa.

Figure 3.33: Manifold cleaning process, (a) manifolds connected to the hydraulic pump, and (b) scheme of the cleaning plates.

Once the servovalves are mounted over manifolds, hydraulic actuators are connected to the fittings mounted on the flange plate (Figure 3.32.d), and every hydraulic connection is verified under operating pressure to detect any oil leakage.

The wire harness is also verified and routed strategically to avoid direct contact with hydraulic hoses, which are a source of vibrations and heat. The aluminium structure acts as a heat sink, transferring the heat generated by the hydraulic system to surrounding water, which acts as a natural coolant fluid.

The embedded controller, in contact with such structure, presents an onboard sensor to monitor the operating temperature (between -40°C and 70°C) which is, therefore, the operating range of the robot prototype.

For high depth applications, the UCU can be filled with mineral oil to compensate the external pressure. However, electrolytic capacitors with paper film must be replaced by equivalent solid-state capacitors to avoid electrical failures.

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Figure 3.34: Electrical underwater connector, (a) male and female connectors, (b) close procedure of the hydraulic fitting, and (c) detail of the pin connectors and JIC bulkhead fitting.

Umbilical cable, sensors, and actuators of the robot are connected to the underwater control unit by means of electrical connectors designed for underwater operation, which are described in Section 3.4.3.

As observed in Figure 3.34, the electrical underwater connectors are made by combining 3D printed parts and hydraulic fittings. The connector has 37 pins and can be adapted for high power cables by grouping several pins. Figure 3.35 shows the control unit with 8 EUC for power supply and data communication.

Figure 3.35: Pictures of the robot prototype during the wiring and commissioning phase. Electrical underwater connectors are, (a) disconnected, and (b) connected and sealed.

3.8 DiverBot Prototype

The underwater anthropoid robot developed in this research work is named DiverBot, referring a diver robot or robotic diver. The design and development process, from first drafts until the first completely functional prototype, takes more than three years, and is shown succinctly in the following pictures.

Figure 3.36 presents different parts of the robot body during assembly at the Centre for Automation and Robotics* (CAR) UPM-CSIC. The mechanical structure uses several laser and waterjet cutting parts fabricated on request at DoHer[†], while machined and 3D printed parts are fabricated at CAR.

Figure 3.36: Robot body development, (a) anthropomorphic hands and forearms, (b) legs and torso assembly, (c) UCU vessel after welding, (d) and (e) assembly process, and (f) robot structure after assembly.

*<http://www.car.upm-csic.es/>

[†]<http://www.doher.es/>

3. Hardware Architecture of an Underwater Anthropoid Robot

System integration requires a synergistic combination of mechanical, hydraulic, and electronic components, since the robot hardware depends of the correct operation of several sensors, servovalves, actuators, and mechanisms. Figure 3.37 shows parts of the commissioning process carried out at CAR.

DiverBot prototype is shown in Figure 3.38 under different configurations. The upper pictures are taken at the 2015 European Researchers' Night at UPM. The pictures on the middle are from a technical demonstration at 2014 IEEE-RAS International Conference on Humanoid Robots. The lower pictures are taken at the test area before the first immersions.

Figure 3.37: Wiring and commissioning, (a) controller and signal conditioning boards, (b) underwater control unit integration, (c) hydraulic tests using the control unit, (d) verification of the whole system, (e) assembled prototype in vehicle configuration, and (f) assembled robot in anthropoid configuration. Total mass: 183kg.

3.8 DiverBot Prototype

Figure 3.38: DiverBot prototype in different configurations, (a) frontal view, (b) and (c) perspective views, (d) folded legs and straight arms before immersion, (e) sitting down on the ground, (f) standing up on the rear legs, (g) and (h) vehicle mode.

3.9 Conclusion

The purpose of this chapter has been to describe the design and fabrication of a hydraulic robot diver with anthropoid structure, adapted for works in underwater environments harmful for people. The underwater robot can be configured under two different functional modes depending on the mission.

The vehicle mode allows the robot to displace through the water with minimum energy, while the anthropoid mode enables the robot to perform dexterous underwater works as a robotic diver. The robot can be controlled by means of an umbilical cable which links the system to a remote control station.

Along this chapter, the hardware design was described by partitioning the system into different modules. The head was designed to house a pan-tilt-zoom dime camera in a strategic position within the robot structure.

The robot torso was realized to house the head, robot limbs, ballasts and propulsion systems, as well as the underwater control unit, charged of the joints and thrusters control. The robotic arms and legs, were designed with anthropoid proportions and hydraulic actuators for underwater operation, allowing to adapt for the physical constraints imposed by both functional modes.

The developed underwater control unit constitutes a complete module which can be used for actuation of any hydraulic machine. The developed prototype, named DiverBot, integrates the control unit with the robot structure.

Along this research, DiverBot is used as a research platform for software development and control studies in order to achieve a proof-of-concept by means of a real prototype, whose validation is performed along the tests carried out in Chapter 7. Software architecture and basic control schemes are treated in the subsequent chapters, while future developments are mentioned in Chapter 8.

*Nothing resolves design issues like an
implementation.*

Joseph D. Horton

Chapter 4

Software Architecture of an Underwater Anthropoid Robot

This chapter describes developed software for handling the sensors and actuators of the underwater robot presented in previous chapter. The software system architecture is described and the software requirements are stated, considering that the robot is remotely operated by a human pilot. Implemented software for each robot component is presented along three functional categories *i.e.*, camera, rotational joints, and propulsion system. Finally, the graphical user interface is described and the conclusions of the chapter are given.

4.1 Introduction

The hardware architecture of an underwater anthropoid robot is described in the precedent chapter. The developed prototype implements several sensors and actuators connected to an on-board programmable automation controller, which communicates with a control station through an umbilical cable.

4. Software Architecture of an Underwater Anthropoid Robot

This chapter is focused on the development of a software system that enables teleoperation of all components of the DiverBot prototype. Hence, a human pilot can send commands to the actuators, and monitor sensor readings to perform underwater intervention tasks from a surface control station.

The underwater robot is fitted with a reconfigurable real-time controller (cRIO) produced by National Instruments. Therefore, the LabVIEW development environment is used to program both embedded and high-level software, using a common visual programming language (*i.e.*, G language), which has an extensive support for accessing hardware devices and third-party instrumentation.

Section 4.2 describes the overall system architecture, and presents functional and non-functional requirements of the software system. The developed programs to manage robot camera, hydraulic rotational joints, and electric propulsion system are described on Sections 4.3, 4.4, and 4.5, respectively. The graphical interface of the robotic diver is depicted in Section 4.6. Finally, conclusions of the chapter are summarized on Section 4.7.

4.2 Software Requirements

Despite a large advent of agile development methodologies, the software system described in this chapter follows a traditional approach, known as waterfall development, which includes sequential phases of specification, development, and validation (Sommerville, 2011). Such methodology is suitable for this application because the software requirements are completely defined by the hardware system and do not change along software development. The requirements stated in this section follow the concepts presented in IEEE Std 830-1998 “Recommended Practice for Software Requirements Specifications” (IEEE, 1998).

4.2.1 Overall Description

As represented in Figure 4.1, the robotic diver is operated by a human pilot to realize underwater operations. The instructions are processed by a host computer which communicates with the robot controller to send commands to the actuators and send back data from sensors to the operator.

Figure 4.1: Scheme of components managed by the software system to enable remote operation of the underwater anthropoid robot from a control station (EMD: external master device).

High-level software executes in a host computer located at control station, and includes all programs related to the user interface. The main functions include displaying data from robot sensors, receive the operator inputs through its peripherals, and send the corresponding commands to the robot controller.

The host computer used on this application is a desktop PC which features a 3.07GHz Intel Core i7-950 processor, 12GB of RAM, and a hard disk of 2TB. The installed operating system is Microsoft Windows 8.1 Pro.

Embedded software executes in the CompactRIO controller including a real-time processor and an FPGA target. The controller receives data from the host computer, captures information from the robot sensors, and sends commands to the robot actuators through the I/O modules (see, Section 3.4.2).

The cRIO controller runs LabVIEW software on the Wind River VxWorks real-time operating system (RTOS). LabVIEW programs are automatically compiled into machine code for VxWorks, and hardware description language (HDL) for the Xilinx FPGA during deployment of the code to the cRIO target. The programming is done at host level and is deployed on the cRIO via Ethernet.

An important part of the software requirements can be obtained by drawing

4. Software Architecture of an Underwater Anthropoid Robot

Figure 4.2: Activity diagram describing the processing flow of robot components. Some sensors and actuators are connected by mechanical devices, (a) pan-tilt mechanisms and zoom lens unit, (b) hydraulic mechanisms of robot head and limbs, (c) robot structure.

schematic diagrams using the notation of the unified modelling language* (UML). The activity diagram of Figure 4.2 represents the processing flow of all sensors and actuators, which are grouped in three functional categories *i.e.*, the robot camera, hydraulic rotational joints, and electric propulsion system.

The UML diagram is divided into partitions to indicate the platform where each part of processing is executed. For instance, encoder processing involves all platforms: data acquisition is done at FPGA, angular position is processed in the real-time controller, and obtained angle is displayed at host computer.

4.2.2 Specific Requirements

The main goal is to develop a human-machine interface (HMI) to manage all sensors and actuators of the DiverBot prototype. Thus, a set of low-level functions must be realized to read data from sensors and write commands to the actuators (embedded in cRIO controller). The HMI is executed in the host computer and must process operator inputs, send the corresponding instructions to the robot controller, and organize the information provided by the sensors.

Additionally, a joystick or any master device must be integrated to the host computer to facilitate interaction with the interface. The user interface must be updated at least each 100ms to allow a natural interaction. Functional requirements related to robot components are listed in Table 4.1.

The real-time controller provides a uniform update rate, which is interesting for the implementation of control algorithms described in next chapters. Considering that the robot is designed for low speed motion in a high density environment, the system bandwidth is assumed to be relatively low. To allow an accurate control, the controller frequency must be higher than the system bandwidth, thus, an update rate of at least 50ms is adopted for this application.

Additional functionalities can be included provided all basic requirements are met. Software implementation using LabVIEW language is described in the following sections. The programs shown are sections of the software used by the robot, and are presented according to the processing flows of Figure 4.2.

*A complete description can be found in (Rumbaugh et al., 2004).

4. Software Architecture of an Underwater Anthropoid Robot

Table 4.1: Functional requirements of the software system.

No.	Description	Target
*	<i>PTZ Dome Camera:</i>	
1.1	Display the acquired image on the user interface.	Host
1.2	Request horizontal pan motion to the camera.	Host/RT
1.3	Request vertical tilt motion to the camera.	Host/RT
1.4	Adjust zoom level on the camera lens.	Host/RT
1.5	Adjust angular velocity of the camera.	RT
*	<i>Hydraulic Rotational Joints:</i>	
2.1	Enable/disable any flow control servovalve.	Host/RT
2.2	Enable/disable all servovalves simultaneously.	Host/RT
2.3	Send $\pm 10V$ commands to each enabled servovalve.	Host/RT
2.4	Send clock signal to the absolute encoders.	FPGA
2.5	Read data signal from the absolute encoders.	FPGA
2.6	Calculate the angle corresponding to each encoder.	RT
2.7	Adjust calculated angular positions.	RT
2.8	Display angles of each encoder on the user interface.	Host
*	<i>Electric Propulsion System (Actuators):</i>	
3.2	Enable/disable any thruster.	Host/RT
3.1	Enable/disable all thrusters simultaneously.	Host/RT
3.3	Send PWM commands to enabled thrusters.	Host/RT
3.4	Request horizontal surge motion to enabled thrusters.	Host/RT
3.5	Request vertical heave motion to enabled thrusters.	Host/RT
3.6	Request heading motion to enabled thrusters.	Host/RT
*	<i>Electric Propulsion System (Sensors):</i>	
4.1	Read attitude information provided by the IMU.	RT
4.2	Define current orientation as a zero reference.	Host/RT
4.3	Display robot orientation on the user interface.	Host
4.4	Read the pressure sensor and calculate current depth.	RT
4.5	Adjust calculated depth values.	RT
4.6	Display robot depth on the user interface.	Host

4.3 PTZ Dome Camera

As mentioned in Section 3.3, the robot head is fitted with a pan-tilt-zoom dome camera to provide visual feedback to a human operator. According to the requirements stated in Section 4.2, the operator controls the camera motion, while the acquired image is displayed into the user interface (see, Figure 4.3).

Figure 4.3: Use case diagram of the camera software. The human operator is represented by two different actors *i.e.*, pilot and administrator.

The pilot can move the camera and adjust zoom level to observe the underwater environment from the robot perspective. The camera has on-board electronics to control three stepper motors according to the input commands, transmitting continuously the acquired image to the host computer through the umbilical cable. For this application, camera motion is configured at maximum speed by the administrator, who can also send motion commands to test the system.

4.3.1 Image Acquisition

The dome camera possesses a Sony CCD chipset with horizontal resolution of 420TV lines. The output video signal is transmitted through a coaxial cable, plugged to the host computer using a USB video capture interface EzCAP116*.

*<http://www.ezcap.tv/usb-video-capture/ezcap116-capture-card>

4. Software Architecture of an Underwater Anthropoid Robot

Figure 4.4: LabVIEW program for image acquisition executed in host computer. Camera (a) and image (b) initialization, get image data (c), arrange image data (d), display image (e), and camera close (f).

As shown in Figure 4.4, the image acquisition software is implemented in a LabVIEW program divided into 3 sequential parts. In the first part, a library function connects with the camera and creates a data structure (a), while another memory location is created for an image with the desired resolution (b).

During the second part, a library function is continuously called inside a while loop to read the last frame, which is stored into an array of blue-green-red pixel values (c), the pixel values are rearranged into a 2D array of RGB color values (d) which are used to create a color image with the user interface dimensions (e).

Once the while loop is stopped, another library function is called to release the memory used by data structure (f). All these functions for video image acquisition are included into a DLL based on OpenCV library (Bradski and Kaehler, 2008).

4.3.2 Motion Commands

Pan-tilt-zoom commands are transmitted by RS485, through the module NI 9871 fitted on cRIO controller (Table 3.7). The camera controller receives PTZ commands according to Pelco D protocol*, which is summarized in Table 4.2. The synchronization byte is always a hexadecimal value FF. The second byte is a log-

*<http://bruxy.regnet.cz/programming/rs485/pelco-d.pdf>

4.3 PTZ Dome Camera

Table 4.2: Message format in Pelco D protocol.

byte 1	byte 2	byte 3	byte 4	byte 5	byte 6	byte 7		
synch.	address	cmd.1	cmd.2	speed.1	speed.2	checksum		
$\mathbf{FF}_{(16)}$	$\mathbf{01}_{(16)}$	$\mathbf{00}_{(16)}$	$\delta_{(16)}$	$\mathbf{3F}_{(16)}$	$\mathbf{3F}_{(16)}$	**		
** (byte 2 + byte 3 + ... + byte 6) mod $100_{(16)}$								
cmd.2	bit 7	bit 6	bit 5	bit 4	bit 3	bit 2	bit 1	bit 0
$\delta_{(2)}$	$\mathbf{0}_{(2)}$	z.wide	z.tele	t.down	t.up	p.left	p.right	$\mathbf{0}_{(2)}$

ical address of the camera (address range: 01--FF). The checksum byte is the 8 bit modulo 256 sum of payload bytes in the message *i.e.*, byte 2 through 6.

Command.1 is used to configure auxiliary functions, such as auto scan, iris, and focus, which are not used for this application. Command.2 is formed by eight bits that represent the type of requested motion according to Table 4.2. Speed.1 defines the angular speed for pan motion, while speed.2 represents the tilt motion speed, from 0.5 to 50 degrees per second (speed range: $00\text{--}3\text{F}$).

Each type of camera motion is related to a button on the user interface, described in Section 4.7, as well as an input code provided by any master device connected to the host computer *e.g.*, joystick or haptic interface. The relation between input codes and pan-tilt-zoom motion, are defined in Table 4.3 (code numbers depends on the joystick sequence defined by the user).

As shown in Figure 4.5, the operator introduces motion commands using a master device to write the local variable (a), as well as through different buttons (b) arranged on the user interface (Section 4.6). Such inputs are combined into a

Table 4.3: Commands for dome camera motion.

motion	pan		tilt		zoom	
sense	right	left	up	down	tele	wide
$\delta_{(16)}$	$02_{(16)}$	$04_{(16)}$	$08_{(16)}$	$10_{(16)}$	$20_{(16)}$	$40_{(16)}$
code	65536	1048576	16384	262144	8396800	4202496

4. Software Architecture of an Underwater Anthropoid Robot

Figure 4.5: Block diagram for motion command selection executed in host computer. Master device code (a) or user interface buttons (b) produce an identifier (c) to select a suitable PTZ command (d).

boolean array which is converted to a single numerical value (c) used to select the PTZ command corresponding to the user request. Global variables in LabVIEW are implemented as network-published shared variables. Thus, the command is stored in a global variable (d) which is continuously updated.

Data transmission is performed through the program described in Figure 4.6 by means of LabVIEW VISA functions. The serial port is configured at a baud rate of 9600bps (a). Inside a timed while loop, the global variable is continuously concatenated inside a Pelco D message (b), which is send to the RS485 module (c). Once the cRIO loop finishes, the serial port is closed (d).

Figure 4.6: Block diagram for serial data transmission executed in cRIO. Configure serial port (a), insert PTZ command into a message (b), send message to the camera (c), and serial port close (d).

4.4 Hydraulic Rotational Joints

The underwater robot includes multiple rotational joints, where each joint is part of a mechanism driven by a hydraulic cylinder or motor. An electrohydraulic servovalve controls the flow through the actuator, while an absolute encoder measures the angular position of the joint. From a software standpoint, a rotational joint is composed by the input signals of encoders and output commands to the servovalves regardless of the type of actuator or mechanism.

Figure 4.7: Use case diagram of the hydraulic rotational joints.

As shown in Figure 4.7, the operator can activate servovalves and send commands to move the robot actuators in any direction. The pilot reads angular positions of any rotational joint, while the administrator can also adjust such angular values for calculation and calibration purposes.

The software described in this section is used as the base for control software developed on Chapter 5, where underwater walking routines are implemented based on kinematic models and joint-space control.

4.4.1 Joint Angle Measurements

The rotational joints are fitted with single-turn absolute encoders (introduced in Section 3.4.2) that convert each angular position into a specific binary code.

4. Software Architecture of an Underwater Anthropoid Robot

Figure 4.8: FPGA program for clock signal generation and data signal acquisition of one I/O port including six encoders. The first clock rising edge (a) starts data transfer into an array (b), the remaining values are transferred after each rising edge (c). Once the array is filled, a transfer timeout allows the encoder to update data (d).

Output data is transmitted differentially through an SSI interface, which allows point-to-point connection from a master (*i.e.*, cRIO controller) to a slave (*i.e.*, absolute encoder). Encoder position is transmitted through a data signal synchronized by a clock pulse train, which are transmitted according to RS422 standards for improved resistance to electromagnetic interference (Fraba, 2013).

Figure 4.8 presents the SSI timing diagram and part of an FPGA program for data acquisition. The angular position is transmitted in a single data word with the most significant bit (MSB) first. The frame length for a single-turn encoder is 13 bits, for any resolution. For a single encoder, clock and data lines stay high until the first falling edge occurs. After the first rising edge, the MSB is transmitted and stored into an array. Each rising clock edge produces the transmit of a bit (clock signal is generated at 1MHz). When the LSB is transferred, a time delay allows encoder data update before the next clock sequence starts.

As described in Section 3.4.2, two modules NI 9403 are used to read 24 encoders simultaneously. Therefore, the lines of each module are grouped into four digital ports, while acquired bits are stored into four arrays with 13 decimal values, where each decimal value represents six different bits.

4.4 Hydraulic Rotational Joints

Figure 4.9: Block diagram executed in cRIO to process encoder data acquired by the FPGA. Initialize FPGA (a), read encoder data (b), process data (c) and store encoder positions in a global variable (d). When timed loop ends, FPGA is stopped (e) and closed (f).

Real-time controller cRIO-9022 executes the program shown in Figure 4.9, which is divided in three parts. The first part creates a reference of the FPGA program on the cRIO FPGA target, and starts the FPGA program (a).

Inside the timed loop, the controller receives data arrays (b) provided by the FPGA, rearranges data to obtain angular position of every encoder and applies offset-values required by the administrator (c); encoder data is stored into a global variable (d). Once timed loop finishes, the controller stops the FPGA program (e) and closes the reference to the FPGA target (f).

Finally, the program of Figure 4.10 is executed in host computer to continuously read the global variable (a), updated by cRIO controller, and display current angular position on the user interface (b). The same scheme is used to display encoder position of any joint of the underwater anthropoid robot.

Figure 4.10: Block diagram executed in host computer to display joint angles on the user interface. (a) global variable, (b) interface indicator.

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Figure 4.11: Block diagram executed in host computer for writing servovalve commands. User input commands (a) are arranged into an array (b), and then stored into global variables (c) and (d).

4.4.2 Servovalve Commands

Servovalve commands are defined as voltage values ($\pm 10V$) selected by the human operator. Such input values are received by cRIO controller to generate an output voltage signal, which is converted into a $\pm 40mA$ current signal by the circuit presented in Figure 3.17, to adapt to servovalve parameters.

The program of Figure 4.11 updates two global variables with input commands (a). Global variable (c) stores the input value for every servovalve, while global variable (d) is used to disable all servovalves simultaneously.

As can be observed in Figure 4.12, the global variables (a) written in the host loop are continuously accessed inside a timed loop to obtain the corresponding voltage values (b) for each servovalve. Such values are written in one analogue output (c) of module NI 9264 (see, Table 3.7). Both schemes are extended to send commands to the 24 servovalves fitted on the underwater control unit.

Figure 4.12: LabVIEW program, executed in cRIO controller, for reading user commands from global variables (a), writing the corresponding value (b) into analogue output (c).

4.5 Electric Propulsion System

As presented in Chapter 3, the underwater anthropoid robot is fitted with eight electric thrusters to perform different underwater motion, a pressure transducer for depth measurements, and inertial measurement unit for spatial attitude calculation. Thus, the propulsion system software manages input data provided by depth and attitude sensors, as well as output commands for thrusters. The system requirements are represented in Figure 4.13 through a UML diagram.

Figure 4.13: Use case diagram of the propulsion system. The action of thrust forces are reflected on attitude and depth measurements.

The operator requests horizontal and vertical displacements, as well as rotational heading motion through speed commands. To stop or disable a specific thruster, a constant null speed command must be send to the actuator.

Depth and orientation of the underwater robot are continuously updated on the user interface to monitor its current location. The pilot defines a reference attitude (*i.e.*, zero angle orientation), while the administrator can also adjust the zero depth reference by means of a proportionality constant.

4. Software Architecture of an Underwater Anthropoid Robot

These software functionalities are used as a base for the control software developed on Chapter 6, where depth and heading autopilots are implemented for closed-loop maneuvers in vehicle mode.

4.5.1 Depth Measurements

The underwater robot is fitted with a piezoresistive pressure sensor, presented in Section 3.4, which outputs an analogue voltage signal (0...10Vdc) proportional to the pressure exerted by water over an internal diaphragm.

As shown in Figure 4.14, pressure readings are acquired on the upper block diagram, executed in cRIO controller, while calculated depth is displayed on the lower block diagram executed at host computer.

Inside the timed loop, the output voltage provided by the pressure transducer is acquired through an analogue input module NI 9201 fitted in cRIO controller (Table 3.7). Voltage levels are converted into depth values which are stored into a global variable, shared with the host computer. Inside the host loop, depth values are continuously read from the global variable, and continuously displayed on the user interface through an indicator.

Figure 4.14: Block diagrams for depth measurements. Pressure sensor output (a) is adjusted to represent current depth (b), which is stored into a global variable (c), which is continuously accessed to display current depth in a user interface indicator (d).

Depth is calculated from voltage values using three constants defined by the administrator, being the sensor output at surface level (offset), a known depth value (num), and the voltage difference between known and surface levels (den). The linear relation between pressure and depth is presented in Section 6.3.2.

4.5.2 Attitude Measurements

An inertial measurement unit (IMU) is used to obtain the spatial orientation of the underwater robot. The inertial unit, presented in Section 3.4, includes an on-board processor to manage embedded accelerometers, gyroscopes, and magnetometers. The processor calculates orientation using an iterative algorithm described in Section 6.3.1. The computed orientation is transmitted by RS485 through a module NI 9871 fitted on the real-time controller (Table 3.7).

As can be observed in Figure 4.15, serial data acquisition is realized by means of LabVIEW VISA functions. The orientation increments are calculated with respect to an initial attitude defined by the administrator, and the obtained data is stored under two representations *i.e.*, Euler angles and unit quaternions.

The block diagram of Figure 4.16, shows on the user interface the current orientation of the robot in terms of Euler angles. A minimal representation of attitude such as roll-pitch-yaw angles results more intuitive for a human operator than quaternions. Nevertheless, unit quaternions are used for control calculations on Chapter 6, as they lack the singularities of Euler angles.

Figure 4.15: LabVIEW program for IMU data acquisition. Initialize serial port (a), initialize IMU (b), read and process IMU data (c), write current orientation in two global variables (d). Once timed loop finishes, send IMU stop command (e), and close serial port (f).

4. Software Architecture of an Underwater Anthropoid Robot

Figure 4.16: LabVIEW program to display robot orientation. Euler angles are extracted from global variable (a), whose values are shown in degrees on the user interface indicators (b).

4.5.3 Thruster Commands

As presented in Section 3.3.2, eight electric thrusters are used to propel the anthropoid robot through the water. Each thruster includes a brushless motor driven by an electronic speed controller (ESC). A total of eight ESC, mounted on back of the robot structure, regulate the power supplied to each motor according to a pulse-width modulation (PWM) signal. The PWM square wave is generated by cRIO controller through NI 9401 module at 50Hz frequency.

User commands are generated at host computer and executed by cRIO controller, as depicted in Figures 4.17 and 4.18. For space saving, only thrusters from the right-side of the robot are shown, but the schemes are valid for all thrusters.

Figure 4.17: Block diagram for manual control of thrusters executed in host computer. Master device inputs (a) are converted into ± 1 commands (b), which are stored in global variable (c). Active thrusters (d) are defined in global variable (e).

Table 4.4: Commands for underwater motion.

motion	surge	heave	heading	stop
code	8209	8212	8210	8192
throttle	Y	Y	X	—

The operator uses a joystick or any master device to write three local variables of the block diagram shown in Figure 4.17. Each type of motion is related to a specific code (see, Table 4.4), and motion speed is regulated by an horizontal (X) or vertical (Y) throttle value. Depending on the desired motion, some thrusters receive forward/reverse speed commands, while others are kept at zero speed. Further details on robot maneuvers are given in Section 6.4.3.

As shown in Figure 4.18, the cRIO controller receives input data from the host program, and writes the corresponding PWM outputs of module NI 9401. The ESC firmware is configured with a linear throttle/brake curve, thus, acceleration of brushless motor is proportional to the PWM duty cycle.

Thruster controller is adjusted to the joystick throttles, by means of a calibration sequence: turn off ESC, move throttle at full forward position, turn on ESC, move throttle at full reverse position, move throttle at neutral position.

Figure 4.18: Block diagram for manual control of thrusters executed in cRIO controller. Input ± 1 commands (a) of active thrusters (b) are converted into speed commands (c), written on the PWM outputs (d). Speed limits (e) and calibration values (f) can also be configured.

4. Software Architecture of an Underwater Anthropoid Robot

4.6 DiverBot Interface

The host computer programs described on precedent sections are integrated into a single graphical user interface (GUI) satisfying all system requirements. The developed GUI allows a human operator to manage sensors and actuators of the DiverBot prototype from a local machine located at control station.

Human-robot interaction is performed by direct manipulation of the interface elements (*i.e.*, controls and indicators). A snapshot of the user interface is shown in Figure 4.19, and its main parts are described in the following paragraphs.

Figure 4.19: User interface of the underwater anthropoid robot. The upper half shows the image acquired from robot head. The lower half contains several control panels to send commands to the robot actuators, and display data from robot sensors.

DiverBot interface is divided in two parts: the upper half shows fixed elements which are always visible to the operator. The image acquired from robot camera is displayed on the upper left corner, along with an array of buttons to control camera motion (Section 4.3.2). Alongside these controls, robot temperature is continuously updated in a vertical indicator. Calibrate button is used to set a zero reference on attitude readings, and stop button halts software execution.

The lower half is formed by a tab control with seven pages or panels arranged by functional categories. Such structure allows to overlap several controls and indicators in a reduced area. Button next serves to switch displayed page from left to right, however, all pages are executed simultaneously.

Data panel includes controls for recording any program variable into text files, as well as indicators to display the time elapsed on each iteration of host computer and controller loops. Text files are useful for further analysis of experimental results in Chapter 7, while execution times serve to monitor software performance *e.g.*, when adding new functionalities. Typical values for this application are 40ms for cRIO controller loop and around 50ms for host computer loop.

The remaining panels are described in the subsequent sections, while controller and autopilot pages are treated in Chapters 5 and 6, respectively. Show 3D button is used on these chapters to open a three-dimensional view of the robot.

4.6.1 Servovalve Panel

The panel of Figure 4.19 is used for sending commands to any servovalve of the robot. The programs related to this panel are treated in Section 4.4.2.

The operator uses a joystick to select any joint from left or right side of the robot, or even two symmetric joints from both sides (selected joints are pointed out by round LED indicators). Once a valve is selected, an output tension signal can be requested to cRIO controller in order to move a specific actuator.

On the upper left corner, the home button writes predefined tension values for every servovalve to produce a default configuration *e.g.*, vehicle configuration. Alongside, zero button serves to enable or disable all servovalves simultaneously, which results useful to ensure that internal valve components are at rest position (0Vdc) before stopping program execution.

4. Software Architecture of an Underwater Anthropoid Robot

4.6.2 Absolute Encoder Panel

The angles measured by absolute encoders mounted on robot joints, are shown on the panel of Figure 4.20. The block diagrams implemented for joint angle measurements are described in Section 4.4.1.

As in the servovalve panel, encoder values are arranged in two columns and round LED indicators point out the joints selected by the operator. The indicators of column (a) display current angles in degrees corresponding to the right side joints, while those of column (b) corresponds to left side. Grayed indicators (c) are used by control software developed in Chapter 5.

Figure 4.20: Control panel for absolute encoders, (a) right side joints, (b) left side joints, and (c) auxiliary indicators.

4.6.3 Propulsion System Panel

The panel shown in Figure 4.21 allows the operator to send speed commands to any thruster of the robot. As described in Section 4.5.3, thruster speed is controlled through PWM commands (*i.e.*, full forward speed for a duty cycle of 10%, null speed at 7.5%, and full reverse at 5%). These commands are scaled into a range varying from +100% to −100%, being more intuitive for a human pilot.

Figure 4.21: Control panel for the propulsion system, (a) manual command indicators, (b) thruster commands, (c) current heading angle, and (d) current depth position.

The button on the upper right corner, serves to enable or disable all thrusters simultaneously. Below this control, a selector allows to switch speed limits for all thrusters by delimiting the duty cycle range. The upper position allocates maximum speed limits (*i.e.*, full forward at 10% and full reverse at 5%). The lower position allocates minimum speed values (*i.e.*, full forward at 8% and full reverse at 7%), which are useful to avoid motor overheating when performing functioning verifications and the robot is outside the water.

Rounded LED indicators (a) point out the type of motion selected by the pilot, while indicators (b) show the speed level requested to each thruster. Changes in robot location are registered on charts (c) and (d) which are continuously updated with current values of depth and heading angle of the robot, respectively.

For instance, in Figure 4.21 below thrusters R3 and L3 are disabled (zero speed). The pilot requests surge motion in order to realize a forward displacement. Hence, horizontal thrusters R1, L1, R3, and L3 receive a +100% speed command, while, R3 and L3 receive a 0% speed command as they are disabled.

For the prototype developed in this research, thrusters are preferably used for vehicle configurations since the robot is close to neutral buoyancy. However, the thrusters can also be driven in anthropoid mode if required.

4. Software Architecture of an Underwater Anthropoid Robot

4.6.4 Master Device Panel

As mentioned above, the operator uses a joystick to send different commands to the robotic diver. For this application, the selected master device is the DualShock 3 (DS3) controller produced by Sony, as it posses two analogue sticks and several digital buttons to control multiple robot functions. Software required to integrate the DS3 joystick into a host computer program can be downloaded at <https://decibel.ni.com/content/docs/DOC-29627>.

Figure 4.22 shows a panel used to display the commands produced by a local or external master device. The selector (b) serves to connect the robot to a DS3 controller or any external device, such as haptic interfaces or motion capture suits. To be compatible with implemented software, all master devices must generate suitable codes defined for each function of the robot (*e.g.*, Table 4.4).

The analogue sticks generate four numerical values shown on indicators (c), and the combination of pressed buttons produces different numerical codes used as command IDs (d). For instance, when R2 button is pressed, the vertical position of the left hand stick serves to regulate the zoom level of the PTZ camera. However, while L2 and triangle buttons are pressed, the same stick position regulates speed of horizontal thrusters for translational surge motion.

Figure 4.22: Control panel for master device input, (a) DS3 indicators, (b) selectable control, (c) stick values, and (d) digital input values.

4.7 Conclusion

Along this chapter, the software architecture of the underwater anthropoid robot has been described. The software system allows a human operator to manage the sensors and actuators of the DiverBot prototype from a control station.

The camera is used to give visual feedback to the operator, the hydraulic limbs allow locomotion or manipulation tasks, and the propulsion system serves for underwater displacements under a vehicle configuration.

The user interface was presented along with its different control panels. Software validation was carried out during the robot commissioning phase, by taking the requirements as a reference to evaluate system performance.

As in the hardware system, the software has a modular structure allowing to introduce new functionalities to the system. Thus, the developed software can be used to implement control algorithms in the subsequent chapters, as well as to collect the information obtained in the experimental tests.

The software system along with the hardware presented in the previous chapter, constitute a research platform to study underwater operation of the robot in anthropoid and vehicle modes. Hence, the next two chapters deal with control aspects of the underwater robot, such as quadrupedal locomotion treated in Chapter 5, and setpoint regulation schemes developed in Chapter 6.

4. Software Architecture of an Underwater Anthropoid Robot

“Ubi materia, ibi geometria” (Where there is matter, there is geometry).

Johannes Kepler

Chapter 5

Screw-Based Stability Analysis for Underwater Locomotion

This chapter is focused on the analysis of statically stable underwater locomotion assuming a quadrupedal configuration of the robot. A position analysis is carried out to model the kinematics relations between joint-space trajectories and trajectories defined in the operational space, as well as other parameters involved in the stability. The static stability of computed trajectories is verified considering gravitational and buoyancy effects through a method based on screw theory. Finally, the obtained results are implemented into a control software used on experimental tests, and conclusions of the chapter are summarized.

5.1 Introduction

In the previous chapters, the hardware and software systems of an underwater anthropoid robot are presented. As a result, a functional prototype named DiverBot is constructed, including a user interface to manage its sensors and actuators.

5. Screw-Based Stability Analysis for Underwater Locomotion

The robotic diver is intended to perform underwater works in specific work areas, such as submerged structures (*e.g.*, nuclear or offshore facilities) or disaster areas (*e.g.*, oil spills or shipwrecks). For long distance displacements, the DiverBot prototype uses a ROV-like configuration (treated in Chapter 6), while in reduced work areas, where the use of thrusters is risky or impractical, walking or climbing may be necessary for short distance displacements.

The focus on this chapter is on quadrupedal underwater walking, due to the advantages of four-legged machines for locomotion in uneven terrains. The position modelling is developed based on geometric methods (Tsai, 1999). Inverse kinematics is used to solve for joint coordinates from Cartesian trajectories, while forward kinematics is used to realize the opposite calculation process.

Based on kinematics results and mass parameters of the robot, a margin of static stability is defined using the principle of normalized virtual power (Davidson and Hunt, 2004). Such margin is used to determine whether a desired trajectory is feasible without risk of upset. The obtained results are integrated as part of the software architecture of DiverBot, including a kinematics simulator for motion planning, and joint-space controllers for motion control.

This chapter is organized as follows. Section 5.2 presents the adopted reference frames and describes quadrupedal locomotion along with the static stability criterion. A position analysis is realized in Section 5.3 obtaining inverse/forward kinematics models and joint coordinates used for control purposes.

Section 5.4 presents the margin of static stability based on gravity and buoyancy effects using the principle of normalized virtual powers. The obtained models are implemented as analysis and control software presented in Section 5.5. Finally, conclusions of the chapter are stated in Section 5.6.

5.2 DiverBot in Anthropoid Mode

The robotic diver is designed with an anthropoid structure comprising a head, two legs, and two arms. For this application, the weight forces are dominant over the buoyant forces when the robot is in anthropoid mode *i.e.*, negative buoyancy (see, Section 3.2.2). Nevertheless, the stability analysis developed in this chapter can be applied for other prototypes including variable ballast systems.

In this section, functional aspects of robot locomotion are mentioned. The adopted reference systems are presented, and the static stability criterion used for underwater locomotion is introduced.

5.2.1 Knuckle-Walking Locomotion

When exploring difficult access terrains, biological systems appear to be more efficient by using quadrupedal strategies for locomotion. In the case of chimpanzees and other hominids, quadrupedal knuckle-walking locomotion is frequently used for displacements in terrestrial and treelike environments.

The kinematic similarity between quadrupedal and bipedal gait is reflected in the metabolic cost of these locomotor modes. Studies based on treadmill measurements of oxygen consumption in chimpanzees have shown that bipedal and knuckle-walking locomotion requires the same amount of metabolic energy (Taylor and Rowntree, 1973), (Sockol et al., 2007).

In a similar manner, quadrupedal robots are generally better adapted for locomotion in rugged terrains than bipedal ones, or even, wheeled and tracked systems. Between the most advanced quadrupedal robots, the BigDog robot is prepared for dynamic locomotion under extreme conditions (Wooden et al., 2010), and the ape-like robot Charlie is designed for research on multi-locomotion modes for spatial applications (Kirchner and Kühn, 2013). However, neither of these prototypes are designed for underwater operation.

From a hydrodynamic standpoint, any machine moving through the water will undergo a drag force which opposes its motion with a magnitude proportional to the square of its velocity. Hence, it results appropriate to address the issue of underwater locomotion with a quasi-static approach, assuming that motion speed is slow enough to maintain hydrodynamics effects in a minimum. A stability analysis for underwater locomotion can be of particular interest for the DiverBot prototype in order to achieve stable movements.

For this application, the robot locomotion is divided into two phases or types of motion. *Stance phase* involves all torso movements with at least three limbs in contact with the ground, while the *stride phase* includes the movement of any robot limb when the other three limbs are in contact with the ground.

5. Screw-Based Stability Analysis for Underwater Locomotion

Figure 5.1: DiverBot in quadrupedal posture, (a) functional prototype, and (b) schematic diagram indicating reference frames and geometric parameters involved in statically stable locomotion.

The analysis assumes well defined trajectories in Cartesian space as the prototype is not fitted with perception capabilities (*e.g.*, acoustic positioning system). Joint coordinates θ_i are measured by absolute encoders fitted at each joint, while spatial orientation of the robot is measured by inertial sensors (Section 6.3.1).

5.2.2 Earth and Body Reference Frames

The robotic diver is designed to operate under two different modes (*i.e.*, anthropoid mode and vehicle mode). Hence, is important to define a reference system describing the robot motion in 6-DOF for both operational modes in order to have a common representation for the different models developed henceforth.

As described in Chapter 6, the adopted reference system is that used for marine vessels which includes two dextral orthogonal coordinate systems (Perez, 2005), (Fossen, 2002). Being, the north-east-down frame $\{n\} \equiv (O_n, \mathbf{x}_n, \mathbf{y}_n, \mathbf{z}_n)$, which is used as an inertial earth frame for local area navigation, and the body-fixed

frame $\{b\} \equiv (O_b, \mathbf{x}_b, \mathbf{y}_b, \mathbf{z}_b)$, which is fixed to the robot.

The reference frames used in this chapter are shown in Figure 5.1. The origin O_b of the body-fixed frame is located on the intersection between the sagittal plane and the rotation axis defined by the hip joints. Hence, the $\mathbf{x}_b$ -axis is at a positive angle ϑ with respect to $\mathbf{x}_n$ during quadrupedal locomotion.

5.2.3 Static Stability Criterion

The static stability of a legged robot can be determined by the proximity of the vertical line containing the center of gravity with respect to the support polygon formed by all the contact points between the robot and the ground. For statically stable locomotion, the vertical line must be kept inside the support polygon in order to avoid tipping moments (McGhee and Frank, 1968).

As described in (Gonzalez de Santos et al., 2006), several methods have been proposed based on this important principle. Nevertheless, for locomotion in underwater environments other effects have to be considered.

The aquatic environment, hundreds of times denser than the air, increases the resistance to motion and generates upward buoyant forces on any submerged body. For slow speed motion, buoyant forces are dominant over hydrodynamic forces, reducing the effective weight of the robot in water. This increased buoyancy makes water a natural reduced-gravity environment*.

Although such conditions allow the use of gaits that would be unstable in terrestrial environments, an excess of buoyancy can also generate unstable situations, since quadrupedal locomotion is no longer realizable when contact points disappear. Hence, the static stability criterion proposed for this study includes not only gravitational interactions, but also buoyancy.

In the forthcoming sections, the contact points and joint coordinates are obtained from desired trajectories and kinematics models. Then, a margin of static stability is calculated through a screw-based method including gravity and buoyancy effects. Finally, the static stability of desired movements is evaluated off-line by kinematic simulations, before being executed by the robot controller.

*Reduced-gravity models are often used in the study of biological systems, see for instance (Martinez et al., 1998) and (Coughlin and Fish, 2009).

5.3 Closed-Form Position Analysis

Robot kinematics deals with geometric and velocity aspects of motion without considering the causes that produce it. The position analysis focuses on studying the geometric relations between operational and joint coordinates of the robot.

The more extended methods for position modelling include Denavit-Hartenberg, successive screw-displacements, and geometric methods (Tsai, 1999). However, depending on the kinematic structure of the robot it is sometimes not possible to find an analytical solution. For these cases, there exist iterative methods to find numerical solutions *e.g.*, Newton-Raphson, interval analysis (Merlet, 2006).

During quadrupedal locomotion the underwater robot can be described by planar linkages, for which analytical solutions can be derived using geometric methods. Although the obtained models depend on the robot geometry, a closed-form solution is interesting for real-time control implementations, as the results are calculated in a fixed number of operations (*i.e.*, deterministic model).

5.3.1 Vector-Loop Equations

The underwater robot is modelled by a redundant 4RRR parallel manipulator formed by four planar chains with a common moving platform. The robot torso constitutes the moving platform, while the soil forms the fixed platform. In the following sections, the kinematics formulation is developed for the right side limbs. Nevertheless, the obtained results are applicable to the left side limbs, considering the robot symmetry along the sagittal plane. The DiverBot geometry is shown in Figure 5.2, and the geometric parameters are listed in Table 5.1.

Table 5.1: Geometric parameters of DiverBot.

link	foot	calf	thigh	torso	arm	forearm	knuckle
length	ℓ_f	ℓ_2	ℓ_1	ℓ_t	ℓ_3	ℓ_4	ℓ_h
(mm)	294.7	497.3	500.0	903.8*	500.0	743.5	10.0
half-distance between feet: $d_f = 247\text{mm}$, between hands: $d_h = 345\text{mm}$							

* depends on torso geometry (see, Appendix B.1)

Figure 5.2: Schematic diagram for quadrupedal locomotion.

For the purpose of this analysis, it is assumed that no slippage occurs between the foot and the soil, as well as between the hands and the soil. Contact between the knuckles and the soil can be modelled by a rolling contact joint, assuming that there is roll without slipping and that the knuckles present a circular profile.

It can be shown that for long displacements of the torso correspond small rotation angles for the knuckles (compared with other rotational joints). These small angles derive in small horizontal displacements of the rolling joint center, considering that the knuckle radio ℓ_h is smaller with respect to the other links (see, Table 5.1). Hence, a virtual rotational joint (U) and a virtual link ℓ_h are used to model the contact between knuckle and soil.

From the geometry in Figure 5.2, two vector-loop equations are written

$$\overrightarrow{O_b H} + \overrightarrow{H K} + \overrightarrow{K A} + \overrightarrow{A P_f} = \overrightarrow{O_b P_f}, \quad (5.1)$$

$$\overrightarrow{O_b H} + \overrightarrow{H R} + \overrightarrow{R E} + \overrightarrow{E U} + \overrightarrow{U P_h} = \overrightarrow{O_b P_h}. \quad (5.2)$$

Equations (5.1) and (5.2) are used in the subsequent sections to find a closed-form solution to the forward and inverse kinematics problems.

5.3.2 Inverse Kinematics Model

For the inverse kinematics problem, the location of the robot torso and limbs are known, and the joint coordinates θ_1 through θ_{12} are to be found, as depicted in Figure 5.3. For a planar parallel manipulator, a closed-form solution can be derived by operating the vector-loop equations presented above.

Figure 5.3: I/O scheme for the inverse kinematics.

Equation (5.1) can be expressed using homogeneous coordinates as follows

$$\begin{bmatrix} \ell_1 c(\phi_t + \theta_1) + \ell_2 c(\phi_t + \theta_{12}) + \ell_f c(\phi_t + \theta_{123}) \\ d_f \\ -\ell_1 s(\phi_t + \theta_1) - \ell_2 s(\phi_t + \theta_{12}) - \ell_f s(\phi_t + \theta_{123}) \\ 1 \end{bmatrix} = \underbrace{{}^bT(q, {}^n\mathbf{p}_t)}_{{}^b\mathbf{c}_1} \begin{bmatrix} {}^n\mathbf{c}_1 \\ 1 \end{bmatrix}, \quad (5.3)$$

where ci is used as a shorthand notation for $\cos(i)$ and si for $\sin(i)$; also, $\theta_{ij} = \theta_i + \theta_j$, and $\theta_{ijk} = \theta_i + \theta_j + \theta_k$. The position vectors defined in the inertial frame $\{n\}$ are expressed in the robot fixed frame $\{b\}$ by the transformation matrix

$${}^bT(q, {}^n\mathbf{p}_t) = \begin{bmatrix} & -({}^n\mathbf{x}_b)^T({}^n\mathbf{p}_t) \\ {}^bR(q) & -({}^n\mathbf{y}_b)^T({}^n\mathbf{p}_t) \\ & -({}^n\mathbf{z}_b)^T({}^n\mathbf{p}_t) \\ 0 & 0 & 0 & 1 \end{bmatrix} \in \mathbb{R}^{4 \times 4}, \quad (5.4)$$

where ${}^bR(q)$ is calculated as the transpose of rotation matrix obtained through the Rodrigues' rotation formula in terms of unit quaternion $q \in \mathbb{S}^3$ (Section 6.2.2).

The first and third rows of (5.3) are arranged as follows

$$\begin{aligned} -\ell_1 c(\phi_t + \theta_1) - \ell_f c\phi_1 + {}^b\mathbf{c}_{1x} &= \ell_2 c(\phi_t + \theta_{12}), \\ -\ell_1 s(\phi_t + \theta_1) - \ell_f s\phi_1 - {}^b\mathbf{c}_{1z} &= \ell_2 s(\phi_t + \theta_{12}). \end{aligned} \quad (5.5)$$

Summing the squares of the two equations in (5.5) gives a single nonlinear equation

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in θ_1 , such that

$$\underbrace{2\ell_1(\ell_f c\phi_1 - {}^b\mathbf{c}_{1x})}_a \underbrace{c(\phi_t + \theta_1)}_\alpha + \underbrace{2\ell_1(\ell_f s\phi_1 + {}^b\mathbf{c}_{1z})}_b \underbrace{s(\phi_t + \theta_1)}_\alpha = \underbrace{-{}^b\mathbf{c}_{1x}^2 - {}^b\mathbf{c}_{1z}^2 + 2\ell_f(c\phi_1 {}^b\mathbf{c}_{1x} - s\phi_1 {}^b\mathbf{c}_{1z}) - \ell_f^2 - \ell_1^2 + \ell_2^2}_c. \quad (5.6)$$

The obtained expression has the form of transcendental equation

$$a \cos(\alpha) + b \sin(\alpha) = c, \quad (5.7)$$

presented in Appendix B.2, for which corresponds a closed-form solution for θ_1 using the atan2 function and subtracting ϕ_t .

Once θ_1 is known, equations in (5.5) can be rearranged as

$$\begin{aligned} c(\phi_t + \theta_{12}) &= (-\ell_1 c(\phi_t + \theta_1) - \ell_f c\phi_1 + {}^b\mathbf{c}_{1x})/\ell_2, \\ s(\phi_t + \theta_{12}) &= (-\ell_1 s(\phi_t + \theta_1) - \ell_f s\phi_1 - {}^b\mathbf{c}_{1z})/\ell_2, \end{aligned} \quad (5.8)$$

and θ_2 is solved using atan2 function

$$\begin{aligned} \theta_2 &= \text{atan2}(-\ell_1 s(\phi_t + \theta_1) - \ell_f s\phi_1 - {}^b\mathbf{c}_{1z}, \\ &\quad -\ell_1 c(\phi_t + \theta_1) - \ell_f c\phi_1 + {}^b\mathbf{c}_{1x}) - \phi_t - \theta_1. \end{aligned} \quad (5.9)$$

Once θ_1 and θ_2 are known, θ_3 is derived from the robot geometry as

$$\theta_3 = \phi_1 - \phi_t - \theta_1 - \theta_2. \quad (5.10)$$

Equation (5.2) can be expressed using homogeneous coordinates as follows

$$\begin{bmatrix} \ell_t c\phi_t + \ell_3 c(\phi_t + \theta_4) + \ell_4 c(\phi_t + \theta_{45}) + \ell_h c(\phi_t + \theta_{456}) \\ d_h \\ -\ell_t s\phi_t - \ell_3 s(\phi_t + \theta_4) - \ell_4 s(\phi_t + \theta_{45}) - \ell_h s(\phi_t + \theta_{456}) \\ 1 \end{bmatrix} = \underbrace{{}^bT_n \begin{bmatrix} {}^n\mathbf{c}_2 \\ 1 \end{bmatrix}}_{{}^b\mathbf{c}_2}, \quad (5.11)$$

where matrix bT_n corresponds to that presented in (5.4). The obtained equation is operated in the similar manner as (5.3) in order to calculate θ_3 , θ_4 , and θ_5 .

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Hence, for joint angle θ_4 the following equation is derived

$$\begin{aligned}
& 2\ell_3(\ell_h c\phi_2 + \ell_t c\phi_t - {}^b\mathbf{c}_{2x})c(\phi_t + \theta_4) + \\
& 2\ell_3(\ell_h s\phi_2 + \ell_t s\phi_t + {}^b\mathbf{c}_{2z})s(\phi_t + \theta_4) = \\
& -{}^b\mathbf{c}_{2x}^2 - {}^b\mathbf{c}_{2z}^2 - 2\ell_h c\phi_2(\ell_t c\phi_t - {}^b\mathbf{c}_{2x}) - 2\ell_h s\phi_2(\ell_t s\phi_t + {}^b\mathbf{c}_{2z}) \\
& - 2\ell_t(s\phi_t {}^b\mathbf{c}_{2z} - c\phi_t {}^b\mathbf{c}_{2x}) - \ell_h^2 - \ell_t^2 - \ell_3^2 + \ell_4^2,
\end{aligned} \tag{5.12}$$

where θ_4 has a closed-form solution using atan2 function (see, Appendix B.2).

Once θ_4 is known, θ_5 is calculated as follows

$$\begin{aligned}
\theta_5 = \text{atan2}\big(& -\ell_t s\phi_t - \ell_3 s(\phi_t + \theta_4) - \ell_h s\phi_2 - {}^b\mathbf{c}_{2z}, \\
& -\ell_t c\phi_t - \ell_3 c(\phi_t + \theta_4) - \ell_h c\phi_2 + {}^b\mathbf{c}_{2x} \big) - \phi_t - \theta_4,
\end{aligned} \tag{5.13}$$

and θ_6 is calculated from robot geometry as

$$\theta_6 = \phi_2 - \phi_t - \theta_4 - \theta_5. \tag{5.14}$$

In the similar manner, another two vector-loop equations can be developed for the left side limbs in order to solve for θ_7 through θ_{12} . Because of robot symmetry along the sagittal plane, the expressions for the left side joints are the same as those obtained for the right side joints by replacing $({}^n\mathbf{c}_1, \phi_1)$ and $({}^n\mathbf{c}_2, \phi_2)$ in the above equations by $({}^n\mathbf{c}_4, \phi_4)$ and $({}^n\mathbf{c}_3, \phi_3)$, respectively.

5.3.3 Forward Kinematics Model

The forward kinematics problem is solved by means of two different models depending on the type of movements realized by the underwater robot *i.e.*, stance or stride motion. The developed models for each type of motion are depicted in the following paragraphs.

Stance Phase Motion

Stance phase involves all torso movements with at least three limbs in contact with the ground (*i.e.*, seabed). Hence, the forward kinematics problem consists on calculate the position ${}^n\mathbf{p}_t$ and orientation angle ϕ_t of the robot torso (*i.e.*, moving

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platform), given the position, orientation angle, and joint coordinates of at least one robot limb. The calculation scheme for this model is shown in Figure 5.4.

Figure 5.4: I/O scheme for the forward kinematics during stance phase movements *i.e.*, robot torso motion.

The torso orientation angle ϕ_t is derived from the robot geometry represented in Figure 5.2, such that

$$\phi_t = \phi_1 - \theta_1 - \theta_2 - \theta_3. \quad (5.15)$$

Once ϕ_t is known, position vector ${}^b\mathbf{c}_1$ is expressed from (5.1) as follows

$${}^b\mathbf{c}_1 = \begin{bmatrix} \ell_1 c(\phi_t + \theta_1) + \ell_2 c(\phi_t + \theta_{12}) + \ell_f c(\phi_t + \theta_{123}) \\ d_f \\ -\ell_1 s(\phi_t + \theta_1) - \ell_2 s(\phi_t + \theta_{12}) - \ell_f s(\phi_t + \theta_{123}) \end{bmatrix}. \quad (5.16)$$

In order to calculate for torso position, (5.16) is inserted into the following equation obtained from the robot geometry, such that

$${}^n\mathbf{p}_t = {}^n\mathbf{c}_1 - {}^n_bR(q) {}^b\mathbf{c}_1, \quad (5.17)$$

where rotation matrix ${}^n_bR(q) \in SO(3)$ is used to represent the spatial orientation of the robot with respect to the inertial frame $\{n\}$.

In the similar manner, another six expressions can be obtained to solve for ${}^n\mathbf{p}_t$ and ϕ_t from the other limbs in contact with the ground.

Stride Phase Motion

Stride phase includes the movements of any limb with the other three limbs in contact with the ground. The forward kinematics problem consists on calculate the position and orientation angle of each robot limb given the location of the robot torso and the joint angles, as presented in Figure 5.5.

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Figure 5.5: I/O scheme for the forward kinematics during stride-phase motion *i.e.*, robot limbs movements.

Equations (5.1) and (5.2) can be expressed in the inertial frame $\{n\}$ using homogeneous coordinates, such that

$${}^n_bT \begin{bmatrix} \ell_1 c(\phi_t + \theta_1) + \ell_2 c(\phi_t + \theta_{12}) + \ell_f c(\phi_t + \theta_{123}) \\ d_f \\ -\ell_1 s(\phi_t + \theta_1) - \ell_2 s(\phi_t + \theta_{12}) - \ell_f s(\phi_t + \theta_{123}) \\ 1 \end{bmatrix} = \begin{bmatrix} {}^n\mathbf{c}_1 \\ 1 \end{bmatrix}, \quad (5.18)$$

$${}^n_bT \begin{bmatrix} \ell_t c\phi_t + \ell_3 c(\phi_t + \theta_4) + \ell_4 c(\phi_t + \theta_{45}) + \ell_h c(\phi_t + \theta_{456}) \\ d_h \\ -\ell_t s\phi_t - \ell_3 s(\phi_t + \theta_4) - \ell_4 s(\phi_t + \theta_{45}) - \ell_h s(\phi_t + \theta_{456}) \\ 1 \end{bmatrix} = \begin{bmatrix} {}^n\mathbf{c}_2 \\ 1 \end{bmatrix}. \quad (5.19)$$

The position and orientation of the robot torso with respect to the coordinate frame $\{n\}$ is represented by the transformation matrix

$${}^n_bT(q, {}^n\mathbf{p}_t) = \begin{bmatrix} {}^n_bR(q) & {}^n\mathbf{p}_{tx} \\ & {}^n\mathbf{p}_{ty} \\ & {}^n\mathbf{p}_{tz} \\ 0 & 0 & 0 & 1 \end{bmatrix} \in \mathbb{R}^{4 \times 4}, \quad (5.20)$$

where rotation matrix ${}^n_bR(q) \in SO(3)$ is calculated from the Rodrigues' formula in terms of quaternions $q \in \mathbb{S}^3$, as described in Section 6.2.2.

Hence, the foot position ${}^n\mathbf{c}_1$ is directly calculated from (5.18), and the hand position ${}^n\mathbf{c}_2$ is obtained from (5.19).

From the geometry shown in Figure 5.2, it can be observed that the orientation angles ϕ_1 and ϕ_2 are related to the joint angles of the robot by

$$\phi_1 = \phi_t + \theta_1 + \theta_2 + \theta_3, \quad (5.21)$$

$$\phi_2 = \phi_t + \theta_4 + \theta_5 + \theta_6. \quad (5.22)$$

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Table 5.2: Construction parameters of DiverBot.

joint	ankle	knee	torso	shoulder	elbow
angle	β_A	β_K	β_t	β_R	β_E
(rad)	0.6351	0.2230	0.5136*	0.2718*	0.9599

* depends on torso geometry (see, Appendix B.1)

As in the inverse kinematics, another two vector-loop equations can be developed for the left side limbs in order to solve for $({}^n\mathbf{c}_3, \phi_3)$ and $({}^n\mathbf{c}_4, \phi_4)$. Because of robot symmetry along the sagittal plane, the expressions for the left side limbs are the same as those for the right side by replacing $(\theta_1, \dots, \theta_6)$ and (d_f, d_h) in the above equations by $(\theta_7, \dots, \theta_{12})$ and $(-d_f, -d_h)$, respectively.

5.3.4 Setpoint Coordinates

The joint coordinates calculated in both forward and inverse kinematics models, are converted into a reduced set of variables called as *setpoint coordinates*. These angular coordinates represent the values to be used by the joint-space controllers of DiverBot, which are presented in Section 5.5.

Setpoint coordinates $\theta_H, \theta_K, \theta_A, \theta_R$, and θ_E are used to account for construction parameters of the DiverBot prototype listed in Table 5.2, as well as for the mechanical limits of the implemented revolute joints. Hence, the robot limbs are not allowed to move outside a secure range defined for each joint in the case of erroneous calculations or wrong user commands.

Considering that the robot is symmetrical with respect to the sagittal plane, the setpoint coordinates are denoted as θ_i^R for right side joints, and θ_i^L for left side joints. Thus, the coordinates for the right side limbs are calculated as

$$\theta_H^R = \begin{cases} \pi/2 & ; (\theta_1 < 4.1988), \\ 2\pi - \beta_t - \theta_1 & ; (4.1988 \leq \theta_1 \leq 5.7696), \\ 0 & ; (\theta_1 > 5.7696), \end{cases} \quad (5.23)$$

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$$\theta_K^R = \begin{cases} 0 & ; (\theta_2 < 3.3646), \\ \theta_2 - \pi - \beta_K & ; (3.3646 \leq \theta_2 \leq 5.4590), \\ 2\pi/3 & ; (\theta_2 > 5.4590), \end{cases} \quad (5.24)$$

$$\theta_A^R = \begin{cases} 2\pi/3 & ; (\theta_3 < 0.4121), \\ \pi - \beta_A - \theta_3 & ; (0.4121 \leq \theta_3 \leq 2.5065), \\ 0 & ; (\theta_3 > 2.5065), \end{cases} \quad (5.25)$$

$$\theta_R^R = \begin{cases} 0 & ; (\theta_4 < 3.4134), \\ \theta_4 - \beta_R - \pi & ; (3.4134 \leq \theta_4 \leq 4.9842), \\ \pi/2 & ; (\theta_4 > 4.9842), \end{cases} \quad (5.26)$$

$$\theta_E^R = \begin{cases} 11\pi/18 & ; (\theta_5 < 0.2618), \\ \pi - \theta_5 - \beta_E & ; (0.2618 \leq \theta_5 \leq 2.1817), \\ 0 & ; (\theta_5 > 2.1817). \end{cases} \quad (5.27)$$

Expressions for the left side coordinates θ_i^L are obtained by replacing in the above equations $(\theta_1, \dots, \theta_5)$ by $(\theta_7, \dots, \theta_{11})$, respectively. The joint limits and ranges are the same as for the right side joints.

Figure 5.6: Setpoint coordinates for the right side joints.

Figure 5.6 represents the scheme for setpoint coordinates θ_i^R corresponding to the right side leg and arm. It is worth mentioning that there is no setpoint coordinates defined for θ_6 and θ_{12} , since they corresponds to the virtual joints used for kinematics calculations in the precedent sections.

The interest of these coordinates is to prepare the robot to receive a single set of commands independently of the implemented kinematics, in order to protect the system against possible wrong commands. Also, this low-level feature allows to change between several models without modifying the control software.

5.4 Margin of Static Stability

This section presents the margin of static stability (MSS), used to determine the stability of the underwater robot during quadrupedal locomotion.

The tendency of a walking machine to tip over is given by the MSS according to two general measures. The first depends on geometric aspects, is calculated as the minimum distance from the vertical line that contains the center of gravity to the lines of the support polygon (McGhee and Frank, 1968).

The second measure is based on energy. The method presented in (Messuri and Klein, 1985) proposes a MSS computed as the potential energy required to rotate the robot from a stable configuration to a condition of instability.

For this analysis, the screw based method presented in (Davidson and Hunt, 2004) is applied for the underwater case to determine a geometric margin.

Tip over occurs when the robot rotates around any line of the support polygon represented by four unit virtual twists. Such rotation is produced by external forces and couples, which are represented by a total destabilizing wrench. For any configuration, the wrench includes a downward weight force applied on the center of gravity (Section 5.4.1), and an upward force applied on the center of buoyancy (Section 5.4.2). Hence, the MSS is calculated from the virtual twists and wrench through the principle of normalized virtual power (Section 5.4.3).

The method reflects all the three-dimensional relations, and provides accurate measures for the MSS compared with other geometric methods based on projected elements. Besides, it allows to easily include buoyancy effects as part of the total destabilizing wrench, which would be conjectural in energy based methods.

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Figure 5.7: Schematic model for CG calculation, (a) parameters of some links, and (b) virtual serial chain pointing the center of gravity.

5.4.1 Center of Gravity Calculation

In a system of rigid bodies, the center of mass (CM) is calculated as the average of the masses of each body factored by their distances from a reference point, while the center of gravity (CG) is a unique point that describes the response of the system to external forces and couples. For a uniform gravitational field, CM and CG are coincident, and the CG can be calculated as the CM of the system.

As presented in (Espiau and Boulic, 1998), the center of gravity of a kinematic chain can be determined by the end-position of an equivalent virtual serial chain, whose geometric parameters depend on the mass properties and geometric parameters of the original chain. The equivalent virtual chain has the same number of DOF of the original system, being the joint coordinates of the equivalent chain simple functions of the original joint variables.

Based on this principle, a method to obtain the virtual chain or statically equivalent serial chain (SESC) is proposed in (Cotton et al., 2009). Nevertheless, for a given structure there exist multiple equivalent chains that describe the same CG position depending on the selected transformations.

Figure 5.8: I/O scheme for CG calculation.

For the purpose of this analysis, the underwater robot is modelled by a branched kinematic chain containing 11 rigid links (1 for the torso, 3 links for each leg, and 2 for each arm). As shown in Figure 5.7, each link is modelled by a mass m_i , and a local CG represented by vector $\mathbf{n}_i \in \mathbb{R}^3$ in a link-fixed reference frame.

The CG position is computed for any spatial configuration using the robot location and joint values as input (see, Figure 5.8). Hence, the CG coordinates can be expressed using homogeneous coordinates as follows

$$\begin{aligned}
 {}^n\mathbf{p}_{cg} = {}^nT(q, {}^n\mathbf{p}_t) & \left(\frac{m_t}{M} T_t \begin{bmatrix} \mathbf{n}_t \\ 1 \end{bmatrix} \right. \\
 & + \frac{m_1}{M} T_t T_1 \begin{bmatrix} \mathbf{n}_1 \\ 1 \end{bmatrix} + \frac{m_2}{M} T_t T_1 T_2 \begin{bmatrix} \mathbf{n}_2 \\ 1 \end{bmatrix} + \frac{m_3}{M} T_t T_1 T_2 T_3 \begin{bmatrix} \mathbf{n}_3 \\ 1 \end{bmatrix} \\
 & + \frac{m_4}{M} T_t T_4 \begin{bmatrix} \mathbf{n}_4 \\ 1 \end{bmatrix} + \frac{m_5}{M} T_t T_4 T_5 \begin{bmatrix} \mathbf{n}_5 \\ 1 \end{bmatrix} \\
 & + \frac{m_7}{M} T_t T_7 \begin{bmatrix} \mathbf{n}_7 \\ 1 \end{bmatrix} + \frac{m_8}{M} T_t T_7 T_8 \begin{bmatrix} \mathbf{n}_8 \\ 1 \end{bmatrix} + \frac{m_9}{M} T_t T_7 T_8 T_9 \begin{bmatrix} \mathbf{n}_9 \\ 1 \end{bmatrix} \\
 & \left. + \frac{m_{10}}{M} T_t T_{10} \begin{bmatrix} \mathbf{n}_{10} \\ 1 \end{bmatrix} + \frac{m_{11}}{M} T_t T_{10} T_{11} \begin{bmatrix} \mathbf{n}_{11} \\ 1 \end{bmatrix} \right), \tag{5.28}
 \end{aligned}$$

where the homogeneous matrices

$$T_t = \begin{bmatrix} c\phi_t & 0 & s\phi_t & 0 \\ 0 & 1 & 0 & 0 \\ -s\phi_t & 0 & c\phi_t & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \text{and} \quad T_i = \begin{bmatrix} c\theta_i & 0 & s\theta_i & \mathbf{d}_i \\ 0 & 1 & 0 & \\ -s\theta_i & 0 & c\theta_i & \\ 0 & 0 & 0 & 1 \end{bmatrix}, \tag{5.29}$$

are used to transform between the coordinates of each link, and matrix ${}^nT(q, {}^n\mathbf{p}_t)$ presented in (5.20), is used to transform the CG position into n -frame coordinates. The link position vectors $\mathbf{d}_i$ are listed in Tables 5.3 and 5.4, and joint coordinates

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θ_i are the same used for position analysis in Section 5.3.

Inserting the matrices in (5.29) into (5.28) and operating, yields

$$\begin{aligned} {}^b\mathbf{p}_{cg} = & R_t\mathbf{r}_1 + R_tR_1\mathbf{r}_2 + R_tR_1R_2\mathbf{r}_3 + R_tR_1R_2R_3\mathbf{r}_4 \\ & + R_tR_4\mathbf{r}_5 + R_tR_4R_5\mathbf{r}_6 + R_tR_7\mathbf{r}_7 + R_tR_7R_8\mathbf{r}_8 \\ & + R_tR_7R_8R_9\mathbf{r}_9 + R_tR_{10}\mathbf{r}_{10} + R_tR_{10}R_{11}\mathbf{r}_{11}, \end{aligned} \quad (5.30)$$

where the virtual chain parameters $\mathbf{r}_i \in \mathbb{R}^3$ are calculated as

$$\mathbf{r}_1 = \frac{m_t\mathbf{n}_t + (m_1 + m_2 + m_3)\mathbf{d}_1 + (m_4 + m_5)\mathbf{d}_4 + (m_7 + m_8 + m_9)\mathbf{d}_7 + (m_{10} + m_{11})\mathbf{d}_{10}}{M}, \quad (5.31)$$

$$\mathbf{r}_2 = \frac{m_1\mathbf{n}_1 + (m_2 + m_3)\mathbf{d}_2}{M}, \quad \mathbf{r}_3 = \frac{m_2\mathbf{n}_2 + m_3\mathbf{d}_3}{M}, \quad (5.32)$$

$$\mathbf{r}_4 = \frac{m_3\mathbf{n}_3}{M}, \quad \mathbf{r}_5 = \frac{m_4\mathbf{n}_4 + m_5\mathbf{d}_5}{M}, \quad (5.33)$$

$$\mathbf{r}_6 = \frac{m_5\mathbf{n}_5}{M}, \quad \mathbf{r}_7 = \frac{m_7\mathbf{n}_7 + (m_8 + m_9)\mathbf{d}_8}{M}, \quad (5.34)$$

$$\mathbf{r}_8 = \frac{m_8\mathbf{n}_8 + m_9\mathbf{d}_9}{M}, \quad \mathbf{r}_9 = \frac{m_9\mathbf{n}_9}{M}, \quad (5.35)$$

$$\mathbf{r}_{10} = \frac{m_{10}\mathbf{n}_{10} + m_{11}\mathbf{d}_{11}}{M}, \quad \mathbf{r}_{11} = \frac{m_{11}\mathbf{n}_{11}}{M}. \quad (5.36)$$

The total mass of the robot M is computed as the sum of masses of torso, right side limbs, and left side limbs, such that

$$M = m_t + \sum_{r=1}^5 m_r + \sum_{l=7}^{11} m_l. \quad (5.37)$$

Table 5.3: Parameters for right side links.

link	thigh	calf	foot	arm	forearm
θ_i	θ_1	θ_2	θ_3	θ_4	θ_5
$\mathbf{d}_i$	$\begin{bmatrix} 0 \\ d_f \\ 0 \end{bmatrix}$	$\begin{bmatrix} \ell_1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} \ell_2 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} \ell_t \\ d_h \\ 0 \end{bmatrix}$	$\begin{bmatrix} \ell_3 \\ 0 \\ 0 \end{bmatrix}$

Table 5.4: Parameters for left side links.

link	thigh	calf	foot	arm	forearm
θ_i	θ_7	θ_8	θ_9	θ_{10}	θ_{11}
$\mathbf{d}_i$	$\begin{bmatrix} 0 \\ -d_f \\ 0 \end{bmatrix}$	$\begin{bmatrix} \ell_1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} \ell_2 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} \ell_t \\ -d_h \\ 0 \end{bmatrix}$	$\begin{bmatrix} \ell_3 \\ 0 \\ 0 \end{bmatrix}$

(ℓ_i and d_i are given in Table 5.1)

The mass parameters and CG of each link are measured through the CAD model of the robot. The obtained values are verified using a hook scale and approximate measures using a plumb line, taking advantage of the symmetry of the anthropoid robot. The CG calculation is verified with the CAD model for different configurations, and some tests are carried out in vehicle configuration for which a CG position can be easily approximated.

5.4.2 Center of Buoyancy Calculation

The Archimedes' principle states that any submerged body undergoes an upward buoyant force which is proportional to the weight of the fluid displaced by the body. In a system of rigid bodies, the center of buoyancy (CB) is a unique point which can be used to describe the response of the system to external forces and couples produced by the buoyancy effect own of any underwater environment.

Assuming a uniform gravitational field, the CB can be calculated as the CG of the volume of water displaced with the exact shape of the original system (Moore et al., 2010). Hence, it is possible to extend the SESC method to estimate the CB position as the end-position of an equivalent virtual chain.

Figure 5.9: I/O scheme for CB calculation.

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Let w_i be the mass of water displaced by link i when fully submerged, and $\mathbf{n}_i^w$ the center of gravity of the displaced volume of water with the exact shape of the original link i , defined in a link-fixed coordinate frame.

The CB position of the original system defined in the inertial frame by position vector ${}^n\mathbf{p}_{cb} \in \mathbb{R}^3$ can be calculated from Equation (5.30) by replacing parameters m_i and $\mathbf{n}_i$ of the original structure, by w_i and $\mathbf{n}_i^w$, respectively.

The mass parameters w_i are calculated as the volume of each part multiplied by water density, and the CG positions $\mathbf{n}_i^w$ are measured through a modified CAD model where all robot parts are defined with homogeneous water density.

Hence, the CB of the robot is computed for any configuration taking as input its spatial location and joint coordinates (see, Figure 5.9). The CB positions are verified for different configurations with the CG positions provided by the CAD software in order to validate the developed model.

5.4.3 Normalized Virtual Power

A complete measure for the margin of static stability can be determined through the principle of normalized virtual power (Davidson and Hunt, 2004).

The margin is computed for any configuration of the robot in distance units, taking as input the contact points with the ground and the external loads acting on the system (see, Figure 5.10). The method applies for any type of terrain and external load, without requiring force measures at the contact points.

For a quadrupedal robot, four unit virtual twists are defined by the coordinates of the contact points, and a total destabilizing wrench comprising weight and buoyancy forces acting on the system. Then, the normalized virtual power K_{ij} is calculated by the product between virtual twists and wrench. Screw coordinates for twists and wrenches are briefly introduced in Appendix C.

Figure 5.10: I/O scheme for MSS calculation.

Figure 5.11: Schematic diagram of the elements used for the static stability analysis of DiverBot during quadrupedal underwater locomotion in uneven terrain (some vectors are omitted for clarity).

Figure 5.11 represents the underwater robot in a quadrupedal configuration over rugged terrain. The contact points are expressed in the inertial frame by position vectors $^n \mathbf{c}_i \in \mathbb{R}^3$ for $(i = 1, 2, 3, 4)$, while the external loads are represented by vectors $\mathbf{f}_W$ and $\mathbf{f}_B$, which represent the resultant of weight and buoyant forces acting on the robot, respectively. Assuming no sliding at the contacts, a set of reaction forces $\mathbf{f}_1, \mathbf{f}_2, \mathbf{f}_3$ and $\mathbf{f}_4$ counteracts the effect of external loads.

The system becomes unstable when the robot rotates over any of the edges of the support polygon. Hence, each mode of potential instability is represented as a virtual rotation by a unit zero-pitch twist

$$w \mathbb{S}_{ij} = w \begin{bmatrix} s_x & s_y & s_z & s_{ox} & s_{oy} & s_{oz} \end{bmatrix}^T \in \mathbb{R}^6, \quad (5.38)$$

where $ij = 12, 23, 34, 41$ and $w = 1$. The components of $\mathbb{S}_{ij}$ are calculated as the six two-by-two determinants of the following array

$$\begin{bmatrix} 1 & c_{ix} & c_{iy} & c_{iz} \\ 1 & c_{jx} & c_{jy} & c_{jz} \end{bmatrix}, \quad (5.39)$$

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such that

$$s_x = \begin{bmatrix} 1 & c_{ix} \\ 1 & c_{jx} \end{bmatrix}, \quad s_y = \begin{bmatrix} 1 & c_{iy} \\ 1 & c_{jy} \end{bmatrix}, \quad s_z = \begin{bmatrix} 1 & c_{iz} \\ 1 & c_{jz} \end{bmatrix}, \quad (5.40)$$

$$s_{ox} = \begin{bmatrix} c_{iy} & c_{iz} \\ s_y & s_z \end{bmatrix}, \quad s_{oy} = \begin{bmatrix} c_{iz} & c_{ix} \\ s_z & s_x \end{bmatrix}, \quad s_{oz} = \begin{bmatrix} c_{ix} & c_{iy} \\ s_x & s_y \end{bmatrix}, \quad (5.41)$$

where the first and second rows in (5.39) corresponds to the homogeneous coordinates of two adjacent contacts given by position vector ${}^n\mathbf{c}_i$ and ${}^n\mathbf{c}_j$, respectively. The order of points i and j gives the positive sense to the virtual twist about $\$_{ij}$ to cause a tip over according to the right hand rule.

The support polygon varies between four and three contact points during quadrupedal locomotion (*i.e.*, stance and stride phases). Thus, the modes of static instability for three contact points are based on three unit twists $\$_{ij}$.

For instance when the right side leg is lifted, the three modes of instability corresponds to twists $\$_{23}$, $\$_{34}$, and $\$_{42}$. When the left hand is lifted, the corresponding twists are $\$_{12}$, $\$_{24}$, and $\$_{41}$, and similarly for the other limbs.

During quadrupedal locomotion, the underwater robot undergoes a downward force due to its own weight applied on the CG, and an upward buoyant force applied on the CB. The total destabilizing wrench is calculated from the magnitude of the forces applied on the system and their points of application as follows

$$\mathcal{S}' = \begin{bmatrix} \mathbf{f} \\ \mathbf{c} \end{bmatrix} = \begin{bmatrix} {}^n\mathbf{f}_W + {}^n\mathbf{f}_B \\ ({}^n\mathbf{p}_{cg} \times {}^n\mathbf{f}_W) + ({}^n\mathbf{p}_{cb} \times {}^n\mathbf{f}_B) \end{bmatrix} \in \mathbb{R}^6. \quad (5.42)$$

Weight and buoyancy forces are defined in the inertial frame as

$${}^n\mathbf{f}_W = \begin{bmatrix} 0 \\ 0 \\ Mg \end{bmatrix}, \quad {}^n\mathbf{f}_B = \begin{bmatrix} 0 \\ 0 \\ -\rho g V \end{bmatrix}, \quad (5.43)$$

where M is the total mass of the robot, g the acceleration due to gravity, ρ is the water density, and V is the volume of water displaced by the robot. The product ρV equals the weight of water displaced by the robot (see Section 5.4.2).

The position vector ${}^n\mathbf{p}_{cg}$ represents the point of application of the total weight force $\mathbf{f}_W$, which corresponds to the CG of the robot for a given configuration (Section 5.4.1). The position vector ${}^n\mathbf{p}_{cb}$ points where the resultant of buoyant forces

$\mathbf{f}_B$ is applied, which corresponds to the CB of the robot for a given configuration (Section 5.4.2). The total destabilizing wrench describes the resultant of these forces and the couples produced when CG and CB are not coincident.

When the system is loaded by only weight forces, the center of gravity is a point of the screw axis where the wrench applies. Nevertheless, when buoyant forces arise, the CG is no longer a point on the screw axis which can take any position with respect to the unit virtual twists over the support polygon, depending on the forces and couples applied on the underwater robot.

The obtained twists and wrench must be normalized in order to obtain a margin with metrical significance (distance units). Hence, the normalized twist $\mathbf{\$}_{ij}$ is obtained by dividing the coordinates of each virtual twist $\mathbf{\$}_{ij}$ by its coordinates $+(s_x^2 + s_y^2 + s_z^2)^{1/2}$. In the similar manner, the normalized wrench $\mathbf{\$}'$ is obtained from wrench $\mathbf{\$}$. Finally, the normalized virtual power is calculated as

$$[K_{ij}] = [\mathbf{\$}_{ij}]^T \begin{bmatrix} 0_{3 \times 3} & I_{3 \times 3} \\ I_{3 \times 3} & 0_{3 \times 3} \end{bmatrix} [\mathbf{\$}']. \quad (5.44)$$

In this form, the distances K_{ij} from (5.44) are always positive when the robot is statically stable. The magnitude of each virtual power K_{ij} provides an accurate measure for the margin of static stability in underwater conditions.

5.5 Motion Control Software

The models described in precedent sections are implemented as part of the software system of the robot. The developed software includes two fundamental parts, which are used for stable locomotion in underwater environments.

The first part constitutes a kinematics simulator used to determine whether a desired motion sequence is stable or not from a quasistatic standpoint. The analysis is realized off-line, and stable movements are stored as discrete trajectories for each robot joint. The second part deals with setpoint regulation in joint-space using twenty-four PI controllers for position control of all hydraulic joints of DiverBot simultaneously. The computed trajectories are executed with a fixed time base to produce smooth and stable locomotion.

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Figure 5.12: Activity diagram describing the analysis process to find stable trajectories for underwater locomotion.

5.5.1 Kinematics Simulator

As observed in previous sections, several calculations are needed to determine the static stability for an arbitrary robot configuration. Thus, a kinematics simulator is developed in Matlab for stability analysis of quadrupedal locomotion.

The calculation process is detailed in Figure 5.12. An input path is defined in task-space by its parametric equations. Cartesian coordinates are mapped into joint coordinates using the inverse kinematics, and the static margin is determined by applying the screw-based method presented in Section 5.4. The path parameters are modified until the margin becomes positive along the robot motion.

A snapshot of the simulator display is shown in Figure 5.13 for the case of quadrupedal locomotion in flat and sloped terrain using cycloidal paths and constant orientations. The graphs on the upper left and lower left corners display the corresponding joint coordinates and margin of static stability, respectively.

As shown in Figure 5.14, the system becomes unstable during stride motions of the right limbs, hence, desired motion must be improved to avoid overturn.

Once a stable motion is determined, the computed trajectories are used as commands for the real system. Thus, joint coordinates are tracked by the robot controllers to reproduce the desired motion. Experiments with the DiverBot prototype are presented and discussed in Chapter 7.

Figure 5.13: Kinematics simulation display. The axis of the total destabilizing wrench is represented by a dashed vertical line.

Figure 5.14: Computed trajectories and margin of static stability. The use of cycloidal paths provides smooth and continuous trajectories.

5.5.2 Joint-Space Controllers

The computed joint trajectories are tracked by means of a closed-loop position control system which includes controller, servovalve, hydraulic actuator, and encoder. Valve flow is applied to the actuator driving a robot joint, whose angular position is measured by the encoder and compared with desired values by the controller. Resulting error is converted into a current signal that shifts the valve spool, adjusting flow to the actuator to control the robot joints.

The position servo system is shown in Figure 5.15. According to (Jelali and Kroll, 2003), the dynamics of a hydraulic servo-actuator (HSA) can be described by a third order type-I system, assuming that the system presents no leakage and the dynamics of the servovalve is faster enough to be safely ignored.

As demonstrated in (Puglisi, 2016), a classical PI controller could be used for position control. Despite the HSA model presents a pole at the origin, a simple P controller does not eliminate the steady-state error since input step disturbances occur before the integrator producing a ramp disturbance which cannot be rejected by this controller. On the other hand, PD and PID controllers produce noisy outputs which are not suitable for position control (Puglisi et al., 2015).

In order to cancel the steady error, a linear PI controller with anti-windup is implemented for each robot joint. The integrator time constant should be carefully adjusted since a PI controller adds another integrator to the closed-loop system, thus, reducing the system stability. Hence, the controllers are tuned using the Ziegler-Nichols method (Ziegler and Nichols, 1942), which provides an acceptable system performance as observed in Chapter 7.

Figure 5.15: Control scheme for servo position loop.

Figure 5.16: Control panel for hydraulic joints controllers, (a) PID gains of each controller, (b) load joint trajectories from a text file, (c) execute the first setpoint from each trajectory, and (d) start motion.

Figure 5.17: Controllers scheme executed in cRIO, (a) select between manual or closed loop, (b) manual commands, (c) controller gains, (d) desired angular positions, (e) current encoder values, (f) PID algorithm for each joint, (g) control actions, and (h) enable/disable control.

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Figure 5.18: 3D model display for motion control, (a) DiverBot at the beginning of stance motion, and (b) stride motion of the left arm. Current configuration of the robot is displayed by model C, while target or desired configuration is depicted by a virtual robot T.

The joint controllers are implemented in LabVIEW. Figure 5.16 presents a snapshot of the controller panel executed by the host computer. This panel allows the operator to adjust the gains of the twenty-four controllers of DiverBot. On top of panel, three buttons allows the user to load a text file containing the setpoint coordinates for each joint, and manage the execution of such coordinates.

Figure 5.17 presents part of the program executed by the cRIO controller. For space saving, the program is represented for three hydraulic joints (servovalves 1, 2, and 3). Nevertheless, it can be easily extended for any number of joints.

The setpoint coordinates are executed with a fixed time period in order to achieve continuous and smooth motion. Desired and current values are received by cRIO through global variables which are used to compute control actions for each joint using classical PI algorithms. The control actions are converted into analogue output signals which are sent simultaneously to each servovalve.

Additionally, the robot motion is fed back to the operator by means of 3D models created using a LabVIEW simulation utility (see, Section 6.6.2).

As observed in Figure 5.18, two virtual robots are displayed by the host computer. The model identified by letter C represents current configuration of the robot limbs with respect to the torso based on absolute encoders readings.

The virtual robot pointed by letter T represents the target configuration determined by the pre-calculated trajectories. Model T is smaller than C, to give visual feedback of the tracking error, which serves to adjust execution delays between samples of the joints trajectories. This feature is particularly useful for adjusting the system in the experiments presented in Chapter 7.

5.6 Conclusion

Static stability provides an acceptable measure to determine the feasibility of a specific motion. Especially in underwater environments, where slow speed motions are appropriate for reducing drag effects. Hence, is important to define a stability margin adapted for any type of terrain including not only gravitational interactions, but also buoyancy effects present in any submerged system.

This chapter provides the elements to analyse the static stability of the underwater anthropoid robot for quadrupedal locomotion, considering gravitational and buoyancy forces for any type of terrain and robot configuration.

Closed-form solutions were derived for robot kinematics, and calculation of the centres of gravity and buoyancy depending on robot configuration. The static stability was measured by a margin computed through a screw-based method. Finally, a kinematics simulator was implemented to calculate the joint trajectories, tracked by linear controllers included on the software system of DiverBot.

Quadrupedal locomotion experiments are carried out using the DiverBot prototype under water, and the obtained results are presented in Chapter 7.

The proposed analysis applies for other tasks, such as manipulation, climbing, or any situation where at least three contact points exist. It also applies for any legged robot for which the kinematics, weight, and buoyant forces are known.

5. Screw-Based Stability Analysis for Underwater Locomotion

*Essentially, all models are wrong, but
some are useful.*

George Box

Chapter 6

Geometry-Based Control for Maneuvers in Vehicle Mode

This chapter describes the aspects involved in the robot displacement under water, assuming a vehicle configuration (*i.e.*, vehicle mode). The elements used to determine the current and desired location of the vehicle are defined. The sensors involved in the navigation system are presented from a control standpoint. Moreover, the interaction between vehicle and water is analysed, a symmetrical disposal of actuators is presented, and the vehicle propulsion mapping is derived. The setpoint regulation problem is solved for depth and heading control assuming known vehicle geometry and including manual commands. Finally, the theoretical results are implemented into a control software used on experimental tests.

6.1 Introduction

In the precedent chapter, the anthropoid robot is analysed for statically stable knuckle-walking locomotion. This chapter focuses on controlling the propulsion system of the robot in order to realize displacements in vehicle mode.

6. Geometry-Based Control for Maneuvers in Vehicle Mode

The robot is intended to be controlled from a mothership through an umbilical cable, where a human operator sends commands to propel the underwater vehicle to a target position or work area. Autopilots are used for low-level control, allowing the operator to focus on high-level decisions concerning the mission. Most advanced autopilots for marine vessels includes model based controllers *e.g.*, acceleration feedback or linear quadratic regulators (Fossen, 2002).

Along this chapter, motion control of the vehicle is studied based only on geometrical aspects and linear control theory. The interest of a geometry based control lies in their adaptability for vehicles with variable payload whose dynamics is not completely known and can change substantially for different missions.

This chapter is organized as follows. Section 6.2 defines the reference frames of the underwater vehicle, as well as attitude and position error calculation. The instruments used for vehicle control feedback are presented in Section 6.3.

Section 6.4 analyses the forces and moments involved in vehicle motion, and derives a propulsion mapping used for motion control. The proposed controller is described in Section 6.5 using the concepts introduced in the previous sections. The implemented control software is presented in Section 6.6. Finally, conclusions of the chapter are given in Section 6.7.

6.2 DiverBot in Vehicle Mode

The underwater anthropoid robot is designed to transform into a remotely operated vehicle capable to propel itself beneath the water as well as on the water surface, by means of electric thrusters arranged strategically over its structure.

The vehicle mode is optimal in terms of power consumption because frontal area is minimum and, therefore, least power is required for propelling the underwater anthropoid robot under this particular configuration.

The interest on a vehicle configuration arises when the robotic diver displaces long distances (*e.g.*, navigation from a mothership to a specific work area), or when passing through narrow structures (*e.g.*, openings in a shipwreck), where would be difficult to access in anthropoid mode.

Table 6.1: Notation for motions of marine vehicles (SNAME, 1950).

motion		location	velocity	force/couple
translation in the x -direction	<i>surge</i>	x	u	X
translation in the y -direction	<i>sway</i>	y	v	Y
translation in the z -direction	<i>heave</i>	z	w	Z
rotation about the x -axis	<i>roll</i>	φ	p	K
rotation about the y -axis	<i>pitch</i>	ϑ	q	M
rotation about the z -axis	<i>yaw</i>	ψ	r	N

6.2.1 Earth and Body Reference Frames

For underwater vehicles moving in three-dimensional Euclidean space, six independent coordinates are necessary to completely determine the location of the vehicle (Fossen, 2002). The first three coordinates correspond to the position of the vehicle, while the last three are used to describe its orientation.

As listed in Table 6.1, the six different motion components are defined as surge, sway, heave for translational motion, and roll, pitch, yaw for rotational motion.

The position and orientation of a marine vehicle would be described by using two dextral orthogonal coordinate systems (Perez, 2005)

- The north-east-down frame $\{n\} \equiv (O_n, \mathbf{x}_n, \mathbf{y}_n, \mathbf{z}_n)$ also named as earth-frame, is defined on a point of a tangent plane to the Earth's reference ellipsoid WSG84.* The $\mathbf{x}_n$ -axis points towards the North, the $\mathbf{y}_n$ -axis points towards East and the $\mathbf{z}_n$ -axis points downwards normal to the tangent plane.
- The body-fixed frame $\{b\} \equiv (O_b, \mathbf{x}_b, \mathbf{y}_b, \mathbf{z}_b)$ is fixed to the vehicle. In this chapter the origin O_b is assumed to be coincident to the center of gravity of the robot *i.e.*, the frame axes are along the principal axes of inertia. The $\mathbf{x}_b$ -axis points from rear to front, the $\mathbf{y}_b$ -axis points to starboard, and the $\mathbf{z}_b$ -axis points from top to bottom, as shown in Figure 6.1.

*World Geodetic System of 1984, a reference frame for the Earth used in navigation.

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Figure 6.1: DiverBot in vehicle mode, (a) functional prototype, and (b) schematic diagram indicating adopted reference frames and motion variables. Subscript v on vector ${}^n\mathbf{p}_v$ stands for *vehicle*.

6.2.2 Quaternion Attitude Representation

In contrast to position representation which is usually stated in terms of three Cartesian, spherical, or cylindrical coordinates, the representation of orientations (*i.e.*, attitude) is extremely more varied. A complete survey of attitude representations is presented in (Shuster, 1993) and (Diebel, 2006).

A minimal representation of the underwater vehicle attitude can be obtained by using a set of three independent Euler angles $\phi = [\varphi \ \vartheta \ \psi]^T$. However, that minimal description of the orientation suffer from singularities, which are difficult to avoid at control level (Corke, 2011). There exist several singularity-free attitude representations which use a set of $(3 + h)$ parameters related by h constraints *e.g.*, direction cosine matrix and unit quaternions.

Theorem 6.2.1 (Euler's rotation theorem). *Any displacement of a rigid body with one fixed point is equivalent to a single rotation about an axis through the fixed point.*

According to Theorem (6.2.1), the spatial orientation of the vehicle would be represented by four Euler parameters which are a form of unit quaternion

$$\mathbf{q} = [q_0 \ q_1 \ q_2 \ q_3]^T \in \mathbb{S}^3, \quad (6.1)$$

$$q_0 = \cos(\theta/2), \quad (6.2)$$

$$\mathbf{q} = [q_1 \ q_2 \ q_3]^T = \hat{\mathbf{n}} \sin(\theta/2), \quad (6.3)$$

where θ and $\hat{\mathbf{n}}$ are respectively, the rotation angle and the unit vector of an equivalent axis-angle attitude representation. In order to keep three rotational degrees of freedom, the parameters must satisfy one constrain

$$q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1. \quad (6.4)$$

Any physical orientation can be represented by two antipodal quaternions $\pm \mathbf{q}$ because the set of unit quaternions $\mathbb{S}^3$ double covers the set of attitudes $SO(3)$ (Kuipers, 1999). Hence, the angle θ must satisfy $-\pi < \theta \leq \pi$ for uniqueness of the quaternion associated to a given orientation, and the axis $\hat{\mathbf{n}}$ must satisfy $\|\hat{\mathbf{n}}\| = 1$ in order to be a pure rotation (Antonelli, 2006).

A rotation matrix expressed in terms of quaternions can be derived by means of the Rodrigues' formula for spherical displacements (see, Appendix B.3)

$${}^n_b R(\mathbf{q}) = I_{3 \times 3} + 2q_0 S(\mathbf{q}) + 2S^2(\mathbf{q}), \quad (6.5)$$

where $I_{3 \times 3}$ is the identity matrix and $S(\mathbf{q})$ is a skew-symmetric matrix which computes the cross product of $\mathbf{q}$ with any other vector in $\mathbb{R}^3$. Equation (6.5) can be written in matrix form as

$${}^n_b R(\mathbf{q}) = \begin{bmatrix} 1 - 2(q_2^2 + q_3^2) & 2(q_1 q_2 - q_3 q_0) & 2(q_1 q_3 + q_2 q_0) \\ 2(q_1 q_2 + q_3 q_0) & 1 - 2(q_1^2 + q_3^2) & 2(q_2 q_3 - q_1 q_0) \\ 2(q_1 q_3 - q_2 q_0) & 2(q_2 q_3 + q_1 q_0) & 1 - 2(q_1^2 + q_2^2) \end{bmatrix}, \quad (6.6)$$

the rotation matrix ${}^n_b R(\mathbf{q}) \in SO(3)$ represents the orientation of the body-fixed reference frame $\{b\}$ with respect to the earth frame $\{n\}$, and can be used to represent any vector on the vehicle frame relative to the inertial frame.

6.2.3 Attitude Error Calculation

The desired orientation of the vehicle is a constant input determined by a human operator. Therefore, a minimal representation for orientation such as Euler angles result more intuitive than quaternions for user inputs. Once input angles are known, the corresponding quaternion can be obtained by the product of three unit quaternions in terms of Euler parameters (Kuipers, 1999)

$$q_d = q_x q_y q_z = \begin{bmatrix} \cos(\varphi_d/2) \\ \sin(\varphi_d/2) \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \cos(\vartheta_d/2) \\ 0 \\ \sin(\vartheta_d/2) \\ 0 \end{bmatrix} \begin{bmatrix} \cos(\psi_d/2) \\ 0 \\ 0 \\ \sin(\psi_d/2) \end{bmatrix}. \quad (6.7)$$

The current orientation of the vehicle is given by an inertial measurement unit, described in Section 6.3.1. The orientation error $q_e \in \mathbb{S}^3$ representing the necessary rotation to take the vehicle from its current orientation q to the desired orientation q_d can be computed by the quaternion product (Tayebi, 2008)

$$q_e = q_d^* q = \begin{bmatrix} q_{e0} \\ q_{e1} \\ q_{e2} \\ q_{e3} \end{bmatrix}, \quad (6.8)$$

where q_d^* is the conjugate of q_d . The corresponding angle of rotation and unit axis can be extracted from q_e through

$$\theta_e = 2 \operatorname{atan2}(\tilde{q}_{e0}, q_{e0}), \quad (6.9)$$

$$\hat{\mathbf{n}}_e = \mathbf{q}_e (\tilde{q}_{e0})^{-1}, \quad (6.10)$$

$$\tilde{q}_{e0} = +\sqrt{1 - q_{e0}^2}, \quad \mathbf{q}_e = [q_{e1} \quad q_{e2} \quad q_{e3}]^T. \quad (6.11)$$

For control purposes, the attitude error of the vehicle may be represented by a rotation vector $\mathbf{e}_q$, defined as a three-dimensional parameterization of the unit quaternion representation, in which the unity norm constraint is introduced into the parameters of a vector of length θ_e directed along the unit axis $\hat{\mathbf{n}}_e \in \mathbb{R}^3$,

$$\mathbf{e}_q = \theta_e \hat{\mathbf{n}}_e. \quad (6.12)$$

The rotation vector lacks both the singularities of the Euler angles and the quadratic constraint of the unit quaternion (Diebel, 2006). This formulation is interesting for vehicle control since the direction and length of the attitude error vector $\mathbf{e}_q$ represent, respectively, the axis and magnitude of the control torque that must be applied to the vehicle for having zero rotational error.

6.2.4 Position Error Calculation

The current vehicle position is represented in Cartesian coordinates by a vector ${}^n\mathbf{p}_v = [x \ y \ z]^T$ defined with respect to the inertial frame and directed from O_n to O_b . The desired position of the underwater vehicle ${}^n\mathbf{p}_d = [x_d \ y_d \ z_d]^T$ is a constant input provided by a human pilot with respect to the earth frame.

The position error $\mathbf{e}_p \in \mathbb{R}^3$ can be computed as the difference between desired and current position expressed in the vehicle reference frame as

$$\mathbf{e}_p = {}^bR(q) ({}^n\mathbf{p}_d - {}^n\mathbf{p}_v), \quad (6.13)$$

where the rotation matrix ${}^bR(q) = {}^nR(q)^T \in SO(3)$ is used as a coordinate transformation matrix in terms of the current vehicle orientation $q \in \mathbb{S}^3$.

This representation is interesting from the control standpoint since the direction and length of the position error vector $\mathbf{e}_p$ represents, respectively, the axis and magnitude of the control force that must be applied to the underwater vehicle in order to have zero translational error.

6.3 Navigational Instruments

Several instruments are part of the sensory system of the robot for measurement and assistance in navigation as underwater vehicle. Regardless of the control method, sensor feedback information is essential in any control scheme.

This section describes two sensors used for vehicle motion control *i.e.*, an inertial measurement unit (IMU) for computing absolute spatial orientation, and a pressure transducer for depth measurements.

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6.3.1 Inertial Measurement Unit

The underwater vehicle is equipped with a strapdown* inertial measurement unit (IMU) for attitude estimation, formed by a computer that process the signals from three-axis rate gyroscope, accelerometer, and magnetometer. Technological aspects of the implemented IMU are further described in Section 3.4.

The attitude of a rigid body can be represented by a direction cosine matrix $R \in SO(3)$ relating the body-fixed frame with respect to reference frame $\{n\}$ (Titterton and Weston, 2004). In order to update the direction cosine matrix, it is necessary to solve the differential equation of attitude kinematics

$$\dot{R} = R \Omega_{\times}, \quad (6.14)$$

where $\Omega_{\times}$ is a skew-symmetric matrix formed from the elements of the angular velocity vector $\boldsymbol{\omega} = [p \ q \ r]^T \in \mathbb{R}^3$ which represents the turn rate of the body with respect to the $\{n\}$ frame expressed in the body-fixed frame, such that

$$\Omega_{\times} = [\boldsymbol{\omega} \times] = \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix}, \quad (6.15)$$

where the elements p , q , and r are the angular rates of the underwater vehicle around the axes of the body-fixed frame measured by the rate gyros.

Because of power limitations, the maximum rotation speed of the vehicle is smaller than 20 degrees per second (heading motion) and the gyro measurements are acquired at a rate of 50Hz, therefore, $\Delta t = 20 \text{ ms}$.

Hence, the maximum angle variation between samples is smaller than 0.007 radian. For small angle rotations, the update of the direction cosine matrix can be implemented using the following approximation (Fossen, 2002)

$$R_{k+1} = R_k (I + \Omega_{\times} \Delta t). \quad (6.16)$$

The IMU algorithm presented in (Premerlani and Bizard, 2009), computes Equation (6.16) to track the orientation of the vehicle from the signals of rate gy-

*In a strapdown system the inertial sensors are rigidly mounted to the vehicle structure, thus replacing the gimbal mechanisms used by platform systems (Lawrence, 1998).

rosopes. Nevertheless, the elements of the direction cosine matrix can gradually accumulate errors due to numerical integration, gyro drift, and gyro offset.

Hence, the elements of the matrix are computed by rows to reinforce orthogonality, and the reference signals from magnetometer and accelerometer are used to correct the measurements of rate gyroscopes by means of a proportional plus integral feedback controller (Premerlani and Bizard, 2009).

Once the rotation matrix is updated and corrected, the corresponding unit quaternion is extracted by means of a singularity free algorithm (Shepperd, 1978), which takes account of the relative magnitudes of the direction cosine elements.

Thereby, the strapdown IMU outputs a unit quaternion $q \in \mathbb{S}^3$ which represents the current attitude of the underwater vehicle.

6.3.2 Pressure Sensor

The hydrostatic pressure exerted by gravity over a vehicle submerged in calm water increases with depth and equals the static weight per unit area of the water column above the vehicle plus the atmospheric pressure (Moore et al., 2010).

Assuming no gravity variations and constant density throughout the liquid, the absolute hydrostatic pressure can be expressed as

$$P = \rho gh + P_0, \quad (6.17)$$

where ρ is the water density, g is the acceleration due to gravity, P_0 is the atmospheric pressure and h is the depth of the vehicle with respect to the surface.

The underwater vehicle is equipped with a piezoresistive pressure sensor* (presented in Section 3.4) for depth measurement, which outputs a voltage signal related to the measured pressure, such that

$$\begin{aligned} V - V_0 &= \frac{1}{k} (P - P_0) \Rightarrow \\ P &= k (V - V_0) + P_0, \end{aligned} \quad (6.18)$$

*A survey on pressure sensor technology can be found in (Tandeske, 1991).

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where k is a proportionality constant, V is the output voltage, and V_0 is the output of the sensor for ($h = 0$). Substituting (6.18) in (6.17), yields

$$h = \frac{k}{\rho g} (V - V_0) \approx \frac{h_1}{V_1 - V_0} (V - V_0), \quad (6.19)$$

where h_1 is a known depth and V_1 is the corresponding sensor output.

The measured depth h of the vehicle corresponds to the third component z of the current position ${}^n\mathbf{p}_v \in \mathbb{R}^3$. Since the aim is the setpoint regulation for depth and heading, x and y are not considered, and the vehicle position will be computed based only on depth measurements (see, Section 6.2.4)

$${}^n\mathbf{p}_v = [0 \quad 0 \quad h]^T. \quad (6.20)$$

6.4 Force and Moment Balance Equations

This section analyses the forces and moments acting on the vehicle in motion through the water assuming quasistatic equilibrium conditions.

Given that the proposed controller is only based on geometrical aspects, the forces are not directly considered in the control strategy, but are analysed in order to define a relation between the propellers and vehicle motion. Such relation is fundamental for the control scheme proposed in Section 6.5.2.

The underwater robot in vehicle mode can be regarded as a submerged rigid body whose interactions with the surrounding water are represented by a system of forces and couples acting on that body.

According to (Moore et al., 2010), up to five types of forces could influence the movement of an underwater vehicle *i.e.*, weight and buoyancy forces, drag forces, thrust and lift forces*. These forces are applied on different points of the underwater robot thus generating moments along specific directions.

For the purpose of this analysis, the forces exerted on the umbilical cable are considered as an external disturbance of the system. Added-mass and environmental forces are neglected, assuming that the vehicle is moving at constant velocity through calm water (*i.e.*, steady motion or non-accelerating motion).

*Lift forces can be safely ignored in slow-moving vehicles.

Figure 6.2: Restoring forces acting on the underwater vehicle. A righting moment is applied to the robot each time the centres of gravity and buoyancy are not in a common vertical line.

6.4.1 Gravity and Buoyancy

The underwater vehicle is affected by gravity and buoyancy forces which are also known as restoring forces. The Archimedes' principle states that the buoyant force is proportional to the weight of water displaced by the vehicle.

The weight force tends to pull the vehicle downward through the water and is assumed to be concentrated in the center of gravity (CG) defined by position vector $\mathbf{p}_{cg} \in \mathbb{R}^3$. The buoyancy force acting on the vehicle tends to push it straight upward toward the surface and is applied in the center of buoyancy (CB) defined by vector $\mathbf{p}_{cb} \in \mathbb{R}^3$ (see, Figure 6.2). The CB of the vehicle is at the CG of the exact shape of water displaced by the vehicle (Moore et al., 2010).

Given that M is the mass of the vehicle, g the acceleration due to gravity, ρ the water density, and V the volume of the vehicle (SNAME, 1950), weight and buoyancy forces can be represented in the vehicle reference frame as

$$\mathbf{f}_W = {}^bR(\phi) \begin{bmatrix} 0 \\ 0 \\ Mg \end{bmatrix}, \quad \mathbf{f}_B = - {}^bR(\phi) \begin{bmatrix} 0 \\ 0 \\ \rho g V \end{bmatrix}, \quad (6.21)$$

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$${}^b_nR(\boldsymbol{\phi}) = \begin{bmatrix} c\psi c\vartheta & s\psi c\vartheta & -s\vartheta \\ -s\psi c\varphi + c\psi s\vartheta s\varphi & c\psi c\varphi + s\varphi s\vartheta s\psi & c\vartheta s\varphi \\ s\psi s\varphi + c\psi c\varphi s\vartheta & -c\psi s\varphi + s\vartheta s\psi c\varphi & c\vartheta c\varphi \end{bmatrix}, \quad (6.22)$$

where $s(i)$ stands for $\sin(i)$ and $c(i)$ for $\cos(i)$. The rotation matrix ${}^b_nR(\boldsymbol{\phi})$ is expressed in terms of Euler angles and is equivalent to ${}^n_bR(q)^T$ expressed in terms of quaternions in Section 6.2.2. The Euler angle representation is used in this analysis for having a more intuitive interpretation of the results, assuming that the vehicle is kept away of singularities *i.e.*, ($|\vartheta| < \pi/2$).

The vehicle is designed such that the CG and CB are coincident with O_b and $\mathbf{z}_b$, respectively. As suggested in (Fossen, 2002), the underwater robot is adjusted to be slightly positively buoyant such that the vehicle does not spend too much energy to stay submerged, and will surface in case of power failure. Nevertheless, it is possible to assume that the vehicle is close to neutral buoyancy, hence

$$\mathbf{f}_W + \mathbf{f}_B = [0 \ 0 \ 0]^T, \quad (6.23)$$

$$\mathbf{p}_{cg} = [0 \ 0 \ 0]^T, \quad \mathbf{p}_{cb} = [0 \ 0 \ -p_{cb}^z]^T. \quad (6.24)$$

Applying these assumptions to the sum of restoring forces acting on the vehicle, yields a resultant wrench

$$\$_{wb}' = \begin{bmatrix} \mathbf{f}_W \\ \mathbf{p}_{cg} \times \mathbf{f}_W \end{bmatrix} + \begin{bmatrix} \mathbf{f}_B \\ \mathbf{p}_{cb} \times \mathbf{f}_B \end{bmatrix} = -Mg \begin{bmatrix} 0 \\ 0 \\ 0 \\ p_{cb}^z c\vartheta s\varphi \\ p_{cb}^z s\vartheta \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ K \\ M \\ 0 \end{bmatrix}. \quad (6.25)$$

When the vehicle is perturbed away from an equilibrium orientation predefined by design, the restoring forces will tend to bring it back toward the equilibrium.

The interaction of weight and buoyancy forces result in two righting moments K and M which tends to align the vertical direction of both forces into a common line, thus, keeping the vehicle into a horizontal equilibrium orientation and resisting any roll and pitch motion (*i.e.*, $\varphi \rightarrow 0$ and $\vartheta \rightarrow 0$).

6.4.2 Propulsion and Pressure Drag

Thrust forces are energy-requiring propulsive forces used specifically to push the vehicle in a particular direction through the water (Moore et al., 2010). A single screw propeller i produces a thrust force f_T^i and couple c_Q^i , which are expressed as a function of the water density, propeller diameter, rotational speed, and a dimensionless advance number (Newman, 1977).

Pressure drag resists relative motion between the vehicle and the surrounding water, and can be expressed in terms of one dimensionless parameter C_D called the drag coefficient (Fossen, 1994). For instance, when the vehicle translates along $\mathbf{x}_b$ axis, a drag force that resists surge motion arises

$$f_D^x = \frac{1}{2} \rho C_D A^x |u| u, \quad (6.26)$$

where ρ denotes the water density, A^x is the frontal area along $\mathbf{x}_b$ axis, and u is the linear velocity of the vehicle along the $\mathbf{x}_b$ axis (see, Table 6.1).

Thrust creates a force imbalance that accelerates the vehicle in a short period of time, until drag increases and cancel out the effect of the thrust. Steady thrust results in a brief period of acceleration followed by constant speed, which is the result of the balance between thrust and pressure drag (Moore et al., 2010).

6.4.3 Eight-Thruster Arrangement

The propulsion system of the underwater vehicle is made up of eight small-power electric thrusters (*i.e.*, motor + screw propeller) arranged strategically. The vehicle is equipped with four horizontal thrusters oriented along the $\mathbf{x}_b$ axis, and four vertical thrusters directed along $\mathbf{z}_b$, as displayed in Figure 6.3.

The thrusters are symmetrically distributed, being four on the starboard side of the vehicle (two horizontal t_1 and t_3 , two vertical t_2 and t_4), and another four on the port side (two horizontal t_5 and t_7 , two vertical t_6 and t_8). Such arrangement allows translations in surge and heave, and rotational heading motion by combining forward and reverse thrust according to Table 6.2.

Each thruster is described by two vectors $\mathbf{p}_i$ and $\hat{\mathbf{s}}_i$ representing the position and orientation of thruster i relative to the vehicle frame, respectively. The

6.4.4 Vehicle Propulsion Mapping

Being that the position and orientation of each thruster is known, and assuming neutral buoyancy with horizontal attitude, is possible to find the thrust forces required to produce an output wrench $\$'$ acting on the center of gravity of the underwater vehicle, such that

$$\mathbf{f} = [X \ 0 \ Z]^T, \quad \mathbf{c} = [0 \ 0 \ N]^T, \quad (6.27)$$

where the resultant force $\mathbf{f} \in \mathbb{R}^3$ and resultant couple $\mathbf{c} \in \mathbb{R}^3$ correspond to the translational and rotational maneuvers allowed by the vehicle (Table 6.2). Summing all the thrust forces acting on the vehicle, yields a resultant wrench

$$\$' = \sum_{i=1}^8 f_T^i \begin{bmatrix} \hat{\mathbf{s}}_i \\ \mathbf{p}_i \times \hat{\mathbf{s}}_i \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{c} \end{bmatrix}, \quad (6.28)$$

these six linear equations can be written in matrix form as

$$\underbrace{\begin{bmatrix} \hat{\mathbf{s}}_1 & \dots & \hat{\mathbf{s}}_8 \\ \mathbf{p}_1 \times \hat{\mathbf{s}}_1 & \dots & \mathbf{p}_8 \times \hat{\mathbf{s}}_8 \end{bmatrix}}_J \underbrace{\begin{bmatrix} f_T^1 \\ \vdots \\ f_T^8 \end{bmatrix}}_{\mathbf{f}_T} = \begin{bmatrix} \mathbf{f} \\ \mathbf{c} \end{bmatrix}, \quad (6.29)$$

where $J \in \mathbb{R}^{6 \times 8}$ is the Jacobian matrix of the vehicle, which provides a transformation between the output wrench $\$' \in \mathbb{R}^6$ and the thrust forces $\mathbf{f}_T \in \mathbb{R}^8$.

A similar matrix is presented in (Tsai, 1999) in the static analysis of the Stewart-Gough platform, which can be roughly seen as a virtual parallel chain describing the 6-DOF instantaneous motion of the vehicle, where the moving platform represents the vehicle, and the spherical joints represent the thrusters.

The use of Jacobian matrices for control purposes is proposed in (Whitney, 1969) as a motion control algorithm for robot manipulators, named as resolved-rate motion control. The algorithm is extended for the case of redundant robots in (Klein and Huang, 1983), where is described as pseudoinverse control.

This approach can also be applied to other machines, such as underwater vehicles with any number of thrusters. Indeed, the matrix J is widely used for thrust

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allocation of marine vehicles. It is also presented as actuator configuration matrix (Fossen, 1994), thruster configuration matrix (Hanai et al., 2003), or thruster control matrix (Antonelli, 2006). As described in the following section, the Jacobian matrix derived in Equation 6.29 can be used to transform position and attitude errors of the vehicle into thruster control errors (Doniec et al., 2010).

6.5 Underwater Vehicle Control

Motion control of an underwater vehicle consists of determining the necessary control actions to be exerted by the vehicle in order to satisfy a certain control objective *e.g.*, setpoint regulation, trajectory-tracking control. In a setpoint regulation problem the desired position and orientation of the vehicle is a constant input provided by a human operator (Fossen, 2002).

Since all the control actions are produced by thrusters arranged in specific positions and directions, the knowledge of vehicle geometry can be used to control its motion. The control method described in this section is closely related to the works by (Hanai et al., 2003) and (Doniec et al., 2010), but is extended to include manual commands inside the control-loop without need of switching from automatic to manual, thus, allowing human intervention when required.

This could be particularly useful to perform combined maneuvers *e.g.*, the vehicle can control depth and heading automatically while the human operator manually regulates forward motion to get into a shipwreck.

This section is intended to solve the setpoint regulation problem based only on geometrical aspects and using linear controllers. The vehicle geometry is represented by means of matrix J , which is used to map the vehicle errors into thruster commands in an optimal manner. From this approach, two autopilots are derived for depth and heading control including manual commands for surge motion.

6.5.1 Optimal Distribution of Control Errors

The control errors represent the difference between desired and current location of the vehicle. The attitude error $\mathbf{e}_q \in \mathbb{R}^3$ is derived in Section 6.2.3, while the position error $\mathbf{e}_p \in \mathbb{R}^3$ is presented in Section 6.2.4. The transformation matrix

6.5 Underwater Vehicle Control

J obtained in Section 6.4.4, allows to map the actuator space of the underwater vehicle onto its operational space. In order to solve for position and orientation errors by separate, two submatrices are extracted from J such that

$$J_p = [\hat{\mathbf{s}}_1 \ \dots \ \hat{\mathbf{s}}_8] \in \mathbb{R}^{3 \times 8}, \quad (6.30)$$

$$J_q = [\mathbf{p}_1 \times \hat{\mathbf{s}}_1 \ \dots \ \mathbf{p}_8 \times \hat{\mathbf{s}}_8] \in \mathbb{R}^{3 \times 8}. \quad (6.31)$$

Thus, the position and attitude errors of the vehicle can be expressed as

$$\mathbf{e}_p = J_p \mathbf{e}_{tp}, \quad \mathbf{e}_q = J_q \mathbf{e}_{tq}, \quad (6.32)$$

where $\mathbf{e}_{tp} \in \mathbb{R}^8$ and $\mathbf{e}_{tq} \in \mathbb{R}^8$ denote the thruster control errors. The inverse transformation of the expressions in (6.32) allows to compute the control error for every thruster by distributing vehicle errors into each actuator.

As there are eight thrusters for motion in 6-DOF, the vehicle is overactuated in sense of operation in three-dimensional Euclidean space (Fossen, 2002). Thus, the transformation matrices J_p and J_q are non-square because there are more control inputs than controllable DOF, and it is possible to find optimal distributions of the control errors by using the least-squares optimization method.

According to (Fossen, 1994), an explicit solution can be found by using the method of Lagrange multipliers; the Lagrangian is defined as

$$\mathcal{L}(\mathbf{e}_{tp}, \boldsymbol{\lambda}) = \underbrace{\frac{1}{2} \mathbf{e}_{tp}^T \mathbf{e}_{tp}}_{\alpha} + \underbrace{\boldsymbol{\lambda}^T (\mathbf{e}_p - J_p \mathbf{e}_{tp})}_{\beta}, \quad (6.33)$$

where α is a quadratic cost function subject to a single constrain β , and $\boldsymbol{\lambda}$ is the vector of Lagrange multipliers. Differentiating (6.33) with respect to $\mathbf{e}_{tp}$ yields

$$\frac{\partial \mathcal{L}}{\partial \mathbf{e}_{tp}} = \mathbf{e}_{tp} - J_p^T \boldsymbol{\lambda} = 0 \quad \Rightarrow \quad \mathbf{e}_{tp} = J_p^T \boldsymbol{\lambda}. \quad (6.34)$$

The Lagrange multipliers can be obtained from the constrain equation as

$$\mathbf{e}_p = J_p \mathbf{e}_{tp} = J_p J_p^T \boldsymbol{\lambda} \quad \Rightarrow \quad \boldsymbol{\lambda} = (J_p J_p^T)^{-1} \mathbf{e}_p. \quad (6.35)$$

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Substituting (6.35) into (6.34) yields

$$\mathbf{e}_{tp} = (J_p^T (J_p J_p^T)^{-1}) \mathbf{e}_p = (J_p^\dagger) \mathbf{e}_p, \quad (6.36)$$

where the matrix $J_p^\dagger$ is the Moore-Penrose pseudoinverse which computes an optimal closed-form solution of the least-squares optimization problem for position errors. In the similar manner, the matrix $J_q^\dagger$ can be used for attitude errors.

Hence, the thruster control errors can be computed as

$$\mathbf{e}_{tp} = J_p^\dagger \mathbf{e}_p, \quad \mathbf{e}_{tq} = J_q^\dagger \mathbf{e}_q, \quad (6.37)$$

where $\mathbf{e}_{tp} \in \mathbb{R}^8$ is the control error for every thruster on the actuator space due to the position error of the vehicle, and $\mathbf{e}_{tq} \in \mathbb{R}^8$ denotes the thruster control error owing to the orientation error of the underwater vehicle.

The geometric parameters of the propulsion system, listed in Table 6.2, are used to calculate the following transformation matrices

$$J_p^\dagger = \begin{matrix} & \begin{matrix} surge & sway & heave \end{matrix} \\ \begin{matrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \\ t_7 \\ t_8 \end{matrix} & \begin{bmatrix} 0.25 & 0 & 0 \\ 0 & 0 & 0.25 \\ 0.25 & 0 & 0 \\ 0 & 0 & -0.25 \\ 0.25 & 0 & 0 \\ 0 & 0 & 0.25 \\ 0.25 & 0 & 0 \\ 0 & 0 & -0.25 \end{bmatrix} \end{matrix}, \quad J_q^\dagger = \begin{matrix} & \begin{matrix} roll & pitch & yaw \end{matrix} \\ \begin{matrix} t_1 \\ t_2 \\ t_3 \\ t_4 \\ t_5 \\ t_6 \\ t_7 \\ t_8 \end{matrix} & \begin{bmatrix} 0 & -0.17 & -0.95 \\ 0.65 & -0.85 & 0 \\ 0 & 0.04 & -0.83 \\ -0.92 & -0.82 & 0 \\ 0 & -0.17 & 0.95 \\ -0.65 & -0.85 & 0 \\ 0 & 0.04 & 0.83 \\ 0.92 & -0.82 & 0 \end{bmatrix} \end{matrix}. \quad (6.38)$$

Position errors are uniformly distributed by matrix $J_p^\dagger$, over horizontal (t_1 , t_3 , t_5 , and t_7) and vertical thrusters (t_2 , t_4 , t_6 , and t_8). The second column presents null elements since no thruster is fitted along $\mathbf{y}_b$ axis for this prototype.

Attitude errors are distributed by $J_q^\dagger$ according to thruster locations, giving smaller control actions to the thrusters which are close to the CG (*i.e.*, shorter lever arm). Thus, roll motion involves only vertical thrusters, yaw motion is controlled by horizontal thrusters, and pitch motion involves all actuators.

Figure 6.4: Control scheme for the underwater vehicle.

6.5.2 Depth and Heading Autopilots

The proposed control scheme on Figure 6.4 is intended to solve the setpoint regulation problem for the underwater robot in vehicle mode, allowing to introduce manual commands without switch off the automatic controllers.

A human pilot uses a joystick or any master device to specify the desired depth z_d and desired heading angle ψ_d , and can also send a manual command $x_m \in \mathbb{R}$ for translational motion along the $\mathbf{x}_b$ axis (*i.e.*, surge motion).

The current location of the vehicle is measured by two feedback sensors presented in Section 6.3. The pressure sensor measures the current depth $z \in \mathbb{R}$, while the inertial measurement unit calculates current attitude $q \in \mathbb{S}^3$.

The position error of the underwater vehicle $\mathbf{e}_p \in \mathbb{R}^3$ is calculated by comparing current depth and attitude with the setpoint depth z_d , as described in Section 6.2.4. The attitude error $\mathbf{e}_q \in \mathbb{R}^3$ is computed by the difference between current attitude and desired heading, as presented in Section 6.2.3.

During normal vehicle operation, pitch and roll angles are kept close to zero by the action of restoring forces, described in Section 6.4.1. Thus, pitch and roll angles are not regulated by the control system but by the vehicle itself.

Position and attitude errors together with the manual commands are the input of a subsystem for allocation and control depicted in Figure 6.5.

6. Geometry-Based Control for Maneuvers in Vehicle Mode

Figure 6.5: Allocator and controller scheme.

The vehicle errors $\mathbf{e}_p$ and $\mathbf{e}_q$ are transformed into thruster control errors according to the expressions in (6.37). The thruster control error $\mathbf{e}_{tp}$ is the input of a set of eight PID controllers which output a vector $\mathbf{u}_{tp} \in \mathbb{R}^8$ containing the control actions to correct the position error (translational motion). In the same manner, $\mathbf{e}_{tq}$ is the input of another eight PID controllers which output the vector $\mathbf{u}_{tq} \in \mathbb{R}^8$ to correct the orientation error (rotational motion).

The output of every PID is a real number which can vary between -1 and $+1$, where negative values implies reverse thrust, a zero value corresponds to the neutral position (*i.e.*, no thrust), and positive values denote forward thrust.

The amount of thrust required to translate the vehicle along the $\mathbf{x}_b$ axis, is specified by the manual command $x_m \in \mathbb{R}$. As can be seen in Table 6.2, the actuators involved in surge motion are the horizontal thrusters t_1 , t_3 , t_5 , and t_7 (see, Figure 6.3). An allocation vector $\mathbf{a}_x \in \mathbb{R}^8$ is defined in order to distribute the open-loop commands to each thruster, such that

$$\begin{aligned} \mathbf{u}_{tm} &= x_m \mathbf{a}_x, \\ \mathbf{u}_{tm} &= x_m \begin{bmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \end{bmatrix}^T, \end{aligned} \quad (6.39)$$

where $\mathbf{u}_{tm} \in \mathbb{R}^8$ contains the command intensity for every thruster. The allocation vector $\mathbf{a}_x$ has components equal to 1 to select the horizontal thrusters, and 0 for disabling vertical thrusters which are not involved in surge motion. The command x_m is scaled to take values between full reverse (-1) and full forward ($+1$), passing through the neutral position when the joystick is released.

The vectors $\mathbf{u}_{tp}$, $\mathbf{u}_{tm}$ and $\mathbf{u}_{tq}$ are combined into a single output $\mathbf{u} \in \mathbb{R}^8$ to account for position errors, manual commands, and attitude errors. Its components represent the control action for every thruster such that

$$\mathbf{u} = \begin{bmatrix} u_1 \\ \vdots \\ u_8 \end{bmatrix} = \mathbf{u}_{tp} + \mathbf{u}_{tm} + \mathbf{u}_{tq}, \quad (6.40)$$

The speed controller of each thruster i receives the control action u_i and speeds up the electric motor, producing a thrust proportional to the control action.

In the case of large control errors when the vehicle is surging at full thrust, the sum can reach ± 3 . However, a saturation function for each thruster is charged to cut off the sum to be inside $[-1, +1]$ according to the physical limitations of thrusters. In this way, each electric thruster can be regarded as a saturating actuator with a maximum forward (F) and reverse (R) thrust.

The combination of thrust forces $\mathbf{f}_T \in \mathbb{R}^8$, drag forces, restoring forces, and external disturbances generates vehicle motion, thus, changing its position and orientation $\boldsymbol{\eta} = [x \ y \ z \ \varphi \ \vartheta \ \psi]^T$. Such changes continuously measured by feedback sensors which close the control loop.

6.5.3 Anti-Windup PID Controller

Windup phenomenon occurs when a controller with integral action is connected to a system with a saturating actuator. In the case of thrusters, the limitations are given by the maximum speed of the motor that spins the propeller.

When the control action reaches the actuator limits, the integral term may become very large if the controller is not properly designed and may give large transients each time the actuator saturates (Åström and Hägglund, 2006).

The output of the PID controller is calculated as the sum of three terms, and is limited to be inside the range $[-1, +1]$ (NI, 2009)

$$u_k = K \underbrace{(e_d - e_k^*)}_{e_k} + \frac{K}{T_i} \sum_{n=1}^k \left(\frac{e_n - e_{n-1}}{2} \right) \Delta t - K T_d \left(\frac{e_k^* - e_{k-1}^*}{\Delta t} \right). \quad (6.41)$$

6. Geometry-Based Control for Maneuvers in Vehicle Mode

Algorithm 6.1: Integral sum correction (NI, 2009)

```

1:  $u_k^p \leftarrow K e_k$ 
2:  $u_k^i \leftarrow \frac{K}{T_i} \sum_{n=1}^k \left( \frac{e_n - e_{n-1}}{2} \right) \Delta t$ 
3: if  $(u_k^p + u_k^i) > (+1)$  then
4:    $u_k^i \leftarrow (+1) - u_k^p$ 
5: end
6: if  $(u_k^p + u_k^i) < (-1)$  then
7:    $u_k^i \leftarrow (-1) - u_k^p$ 
8: end

```

The first term is proportional to the error, where k is the index of the sampled signal at time kt , and K is the proportional gain. The error for every thruster is zero when the vehicle reaches the desired location, thus, the setpoint value for all actuators is the constant ($e_d = 0$). The error of the i th thruster is expressed as e^* which can refer either a position error e_{tp}^i , or an orientation error e_{tq}^i .

The second term is proportional to the integral of the error, where T_i is the integral time and Δt is the sampling time of the controller. The aim of the integral action is to ensure zero steady-state error. Trapezoidal integration is used to avoid sharp changes when there is a sudden change in the control error.

Several methods are used to avoid windup *e.g.*, back-calculation and clamping (Åström and Hägglund, 2006). The implemented PID controller uses an anti-windup algorithm based on conditional integration (see, Algorithm 6.1).

The third term is proportional to the derivative of the error. Derivative action improves closed-loop stability, and is only applied to thruster errors to avoid derivative kick due to abrupt changes in the setpoint during maneuvers.

However, most remotely operated vehicles for offshore applications use only simple P and PI controllers for automatic heading and depth control, since derivative action can be very sensitive to measurement noise (*i.e.*, $T_d = 0$).

Being that the dynamics and losses of the thrusters as well as dynamic aspects of the vehicle are not directly considered, the use of two PID controllers for each actuator can approximate vehicle dynamics (Doniec et al., 2010).

Thus, PI control is adequate even if the system has higher-order dynamics, what is needed is an integral action to provide zero steady-state error and an adequate transient response by proportional action (NI, 2009).

6.6 Thrust Control Software

The developed control software is depicted in Figure 6.6. Software implementation is done by considering the theoretical framework presented in previous sections, as well as the software architecture described in Chapter 4.

Functions requiring interaction of the operator are executed at host level. Figure 6.7 presents the host computer program, where master device codes and keyboard entries generate depth and heading setpoints, which are stored in variables shared with the cRIO. The input codes produce different increments on the set-point values for closed-loop motion of the robot according to Table 6.3.

Figure 6.6: Activity diagram describing the processing flow of depth and heading autopilots, (e_p) position error, (e_{tp}) thruster control errors due to e_p , (e_q) attitude error, (e_{tq}) thruster control errors due to e_q .

6. Geometry-Based Control for Maneuvers in Vehicle Mode

Figure 6.7: Host computer program to generate setpoint values and display current robot location. Master device input (a) is used to set desired depth (d) and attitude (e). Current depth (b) and current attitude (c) are continuously displayed in the user interface.

Figure 6.8: Setpoint regulation algorithm for two thrusters executed in cRIO. The PID outputs are calculated according to rotation error (a) and translation error (b) of each thruster. PID commands are combined with manual commands (c), and scaled into speed commands (d) which are send to each actuator as a PWM output signal (e).

Table 6.3: Commands for setpoint generation.

motion	sense	big-step	small-step	continuous	zero-value
yaw	right	73904	73776	134225968	8752
	left	1056944	1056816	67117104	
heave	down	270512	270384	16785456	8496
	up	24752	24624	33562672	

On the other hand, functions related to sensors and actuators involved in the control loop are executed at cRIO controller. The implemented control scheme is shown in Figure 6.8. For space saving, the program is presented only for two actuators, but the same scheme can be extended for any number of thrusters.

6.6.1 Autopilot Panel

Controls and indicators of Figure 6.7 are organized on the autopilot panel shown in Figure 6.9, which allows the operator to introduce target values of depth and heading using the keyboard or any master device (*e.g.*, joystick). The round led indicators display manual commands required by the pilot.

Figure 6.9: Control panel for depth and heading autopilots, (a) desired values, (b) manual command indicators, (c) current/desired heading chart, (d) depth chart, and (e) enable/disable autopilots.

6. Geometry-Based Control for Maneuvers in Vehicle Mode

On the lower left corner, the PID gains for thruster control errors allow to tune the system controllers. On the center, two horizontal graphs are continuously updated with temporal evolution of depth and heading. Current values are represented by the straight lines, while the stepped lines depict desired values.

Along the right side there is a button to enable or disable all thrusters simultaneously, and a selector to switch speed limits of thrusters. Below those controls, there is an additional button to enable/disable the autopilots action.

6.6.2 3D Model View

Visual feedback of the robot location is provided to the human operator using a robotics simulation utility programmed in LabVIEW, which can be downloaded at <https://decibel.ni.com/content/docs/DOC-2430>.

The simulator uses parent-child relations between 3D objects, such that when a translation or rotation is applied to a parent object all subsequent child objects experience the same transformation. It allows to import stereolithography files (STL) generated from a CAD software, and also creating basic geometric objects. Front panel controls are available to manipulate the joints between two objects, according to the values provided by an external program.

Figure 6.10: 3D model display for depth and heading autopilots, (a) a 1m vertical translation is send to the controller, (b) a 90° heading rotation is required by the operator. Current location is displayed by robot C, while target location is represented by a virtual robot T.

As observed in Figure 6.10, two virtual robots are created. The robot pointed by letter C represents current location based on attitude and depth readings. The virtual robot T is smaller than C, and represents the target location through the operator commands. Hence, when both models have the same location means that the target was attained and robot T is included into robot C.

The interest of such implementation is to plot the localization error of the robot, assisting the operator to intuitively appreciate system evolution. The 3D view is called by pressing button “Show 3D” of the user interface (shown in Figure 4.19). The image is updated at execution time of the host computer (less than 100ms), giving a realistic representation of robot motion.

6.7 Conclusion

This chapter solves the setpoint regulation problem for the underwater anthropoid robot in vehicle mode, which is an optimal configuration in terms of power consumption for large displacements beneath the water, for instance, to reach a strategic location or work area where a physical intervention is required.

A propulsion map was derived from the robot geometry, and used to control vehicle motion. Depth and heading autopilots were implemented into the robot software system, providing a control panel to request setpoint values combined with manual commands for specific thrusters required by the operator.

Geometry based control is particularly useful for prototypes where the model is continuously changing from one mission to another, since only depend on basic geometric parameters *i.e.*, screw coordinates. Also, the proposed controller can be adapted to any number of thrusters and different vehicle geometries.

The vehicle controller is experimentally verified on Chapter 7, through a set of maneuvers involving depth and heading control combined with surge motion. The autopilots are also tested in the presence of external disturbances, and changes produced by the robot when moving its limbs *i.e.*, internal disturbances.

6. Geometry-Based Control for Maneuvers in Vehicle Mode

“En la cancha se ven los pingos” (Let’s see the horses on the track).

Argentinian Saying

Chapter 7

Experimental Results

This chapter presents the experiments carried out in underwater conditions using the first version of the DiverBot prototype. Some operation tests performed during the design and development phases of hardware and software parts of the robot are briefly mentioned. The experimental setup is described, including power elements, control station, and a water tank allowing full immersion of the robotic diver in calm water conditions. The results of experiments about statically stable underwater locomotion are presented, as well as the experiments for maneuvers in vehicle mode. Finally, the obtained results are summarized and discussed to analyse the performance of the developed underwater robot.

7.1 Introduction

In the precedent chapters, a real prototype of a novel underwater anthropoid robot is presented, and its hardware and software systems are described. Also, control strategies to manage its underwater motion are proposed, being quadrupedal locomotion in anthropoid mode and displacements in vehicle mode.

7. Experimental Results

This chapter brings together the experimental results produced throughout this research work using the robot prototype and the methods presented in previous chapters. Experiments are performed around three general objectives:

- *To demonstrate that DiverBot is prepared for underwater operation.*
- *To achieve underwater motion using the hydraulic actuation system.*
- *To perform underwater displacements using the propulsion system.*

The first requirement is satisfied along the chapter, since experiments are not possible if the anthropoid robot is not completely waterproof even for shallow water use. The last two requirements related with the hydraulic and propulsion systems are treated separately in the forthcoming sections.

Section 7.2 mentions some operation tests carried out during the prototype development phase. The experimental setup used for experiments in underwater conditions is described in Section 7.3. Section 7.4 presents experiments related with statically stable movements under water, and Section 7.5 treats the underwater displacements of DiverBot using the propulsion system under vehicle configuration. Finally, the obtained results are discussed in Section 7.6.

7.2 Preliminary Tests

A complete sealing is instrumental to allow a secure immersion of the robot. Sensors and actuators of DiverBot are waterproof by default, while the sensitive parts such as servovalves and electronic boards are protected against water inside a watertight vessel named underwater control unit (see, Section 3.4).

As additional protection, the control unit is fitted with an air supply providing a small positive pressure. Hence, air pressure pushes water outside the vessel if breaks occur. For deep water applications the use of oil filled elements and pressure compensators is required to protect for external pressure.

Before having a full watertight system, several tests are realized to validate each element of DiverBot. Such operating tests are important to take design decisions along the development phase. The pictures in Figure 7.1 correspond to some of the tests performed before first immersion *e.g.*, electric thrusters are checked at slow speeds to avoid overheating produced outside water.

Figure 7.1: Preliminary tests with the DiverBot prototype, (a) testing hands and hydraulic circuits, (b) readings from absolute encoders, control software (c), and joint-space controllers (d).

7.3 Experimental Setup

As shown in Figure 7.2, the handling equipment of DiverBot consists on a wheeled structure to transport the robot when is not powered, and a jointed beam with a 500kg hoist at the end to place the robot inside a water tank.

The tank is installed at ground level and designed to support a volume of around 16.000 litres water. The lateral sides are made with transparent acrylic plates that allow video capture using conventional cameras from outside the water.

The underwater robot is connected through an umbilical cable to the control station, which includes an electric board for power supply of all robot elements. The hydraulic actuators are powered by a variable displacement pump (Parker PVP23) with a low-pressure stage containing a pressure relief valve for 7MPa supply and a filter to protect servovalves from fluid contamination.

7. Experimental Results

Figure 7.2: Water tank and handling equipment (a), DiverBot in anthropoid mode (b) and vehicle mode (c), electric board and host computer (d), hydraulic filter and valve (e), and hydraulic station (f).

7.4 Underwater Motion in Anthropoid Mode

This section focuses on underwater movements produced by the hydraulic joints of DiverBot. The anthropoid mode results particularly interesting since the robot can be supported through its four limbs using all joints to generate motion.

As presented in Chapter 5, static stability provides an important framework to determine the stability of robot motions developed in reduced gravity conditions. Also, a kinematic simulator is developed to compute the margin of static stability for a given motion, and joint-space controllers are integrated into the software system of the robot in order to execute pre-calculated trajectories.

Hence, two kinds of motion are performed to test the joints along with the scope of the stability methods *i.e.*, standing-up motion and knuckle-walking.

7.4.1 Standing-Up Movement

During the hardware design phase, the standing-up motion is simulated using Adams package to calculate the mechanisms corresponding to the limbs of Diver-Bot and select suitable hydraulic actuators (Section 3.5.1). On this section, the standing-up motion is performed under water using the developed prototype. The obtained results show that DiverBot is capable to support its effective weight in actual operating conditions using only the hydraulic joints.

The configurations required for this motion are determined using the kinematics simulator (Figure 7.3). Simulated and experimental movements are depicted in Figures 7.4 and 7.5, respectively. As observed in Figure 7.6, the MSS is approximately constant along the robot motion since lateral sides of the support polygon are longer than the offset between foot and hand, producing small variations of the minimum distance between the total wrench and lateral twists.

The graphs on Figures 7.7, 7.8, and 7.9 present the measured robot orientation and joint trajectories expressed over time. Time values are estimated based on the average period measured by the robot controller ($\approx 40\text{ms}$). The measured parameters show that, in general, position controllers follow the desired angles correctly with small overshoot and acceptable rise time.

Figure 7.3: Kinematics simulation for standing-up motion.

7. Experimental Results

Figure 7.4: Snapshot sequence corresponding to standing-up movements in horizontal flat terrain. Up and down movements are statically stable because total wrench remains inside the support polygon.

Figure 7.5: Snapshot sequence obtained from standing-up experiments. Robot motion is produced by step inputs applied to all joints simultaneously. Joint values are determined a priori through simulations.

7.4 Underwater Motion in Anthropoid Mode

Figure 7.6: Static stability for the standing-up motion.

Figure 7.7: Time evolution of robot orientation, hip joints, and commands for servovalves during standing-up motion. Pitch angle depends on the displacements of robot links along the sagittal plane, and roll angle holds around zero degrees *i.e.*, symmetrical motion.

7. Experimental Results

Figure 7.8: Time evolution of knee and ankle joints, along with the commands for the respective servovalves during standing-up motion. Since the robot moves in horizontal flat terrain, the angular displacements for right and left side joints are almost equal.

7.4 Underwater Motion in Anthropoid Mode

Figure 7.9: Time evolution of knee joints, ankle joints, and commands for the respective servovalves during standing-up motion. Shoulder joints encounter friction forces produced by the permanent contact between knuckles and soil that slows down setpoint regulation.

7. Experimental Results

7.4.2 Quadrupedal Locomotion

The kinematics simulator is used to calculate the joint coordinates required for locomotion along the $\mathbf{x}_n$ direction (see, Figure 7.10). Cycloidal paths are used to produce forward motion with smooth trajectories in joint-space, whose parameters are adjusted to obtain values inside the joint limits. Regarding the stability of the proposed motion, the static margin is stable during torso and leg movements and becomes unstable for arm movements, as detailed in Figure 7.13.

The aim is to accomplish a stable walking sequence despite unstable parts of motion, considering that DiverBot is in a high-density environment where any motion is damped by action of water. Hence, the arm movements are modified to be executed faster than the rest of movements, taking advantage of the time delay produced under water before overturn begins. Snapshots for simulated and experimental motion are shown in Figures 7.11 and 7.12, respectively.

The graphs on Figures 7.14, 7.15, and 7.16 present the measured torso orientation and joint trajectories expressed over time. Time values are estimated according to the average period measured by the controller ($\approx 40\text{ms}$). The obtained results show that position controllers regulate the desired joint values correctly, making possible stable locomotion of DiverBot under water.

Figure 7.10: Kinematics simulation for quadrupedal locomotion.

7.4 Underwater Motion in Anthropoid Mode

Figure 7.11: Snapshot sequence corresponding to quadrupedal locomotion of DiverBot in horizontal flat terrain. Total destabilizing wrench holds inside the support polygon for almost all parts of motion.

$$(A) \equiv (0m, 0s) \longrightarrow (B) \equiv (1.2m, 147s)$$

Figure 7.12: Snapshot sequence obtained from knuckle-walking experiments. DiverBot performs a sequence of four steps to displace from (A) to (B) at slow speed. Robot motion is generated by tracking the joint coordinates calculated by the kinematics simulator.

7. Experimental Results

Figure 7.13: Static stability for quadrupedal locomotion (parts of motion which are potentially unstable are highlighted by ellipses).

Figure 7.14: Time evolution of robot orientation, hip joints, and commands for servovalves during quadrupedal locomotion. Pitch and roll angles maintain around zero degrees *i.e.*, stable motion.

7.4 Underwater Motion in Anthropoid Mode

Figure 7.15: Time evolution of knee and ankle joints, along with the commands for the respective servovalves during knuckle-walking locomotion. To increase speed, right leg motion is performed during the stance phase motion using three contact points instead of four.

7. Experimental Results

Figure 7.16: Time evolution of knee joints, ankle joints, and commands for the respective servovalves during knuckle-walking locomotion. Shoulder and elbow joints are moved in a short period of time in order to minimize the effect of unstable parts of motion.

As observed in previous graphs, the stance phase is modified with respect to the simulations to be executed using only three contact points (*i.e.*, right and left arms and left leg), which allows to overlap the right leg motion during torso movement in order to increase the speed of forward displacement. For the same reason, joint trajectories are replaced during the stride phase by step inputs whose values are extracted from final values of computed trajectories.

7.5 Underwater Maneuvers in Vehicle Mode

This section focuses on underwater movements produced by the electric thrusters of DiverBot (*i.e.*, underwater maneuvers). As mentioned earlier, the vehicle mode results efficient in terms of energy for long distance displacements since frontal area is minimized and the robot is almost neutrally balanced.

Control aspects of the robot under vehicle configuration are treated in Chapter 6. The propulsion system comprises eight thrusters arranged along the robot structure according to the scheme of Figure 7.17, allowing heave, surge, and heading motion (see, Table 6.2). A control strategy is developed using PI controllers along with a model of the robot based on geometric parameters to distribute control errors along the propulsion system in a least-squares manner.

The purpose of the following experiments is therefore to validate the correct performance of the buoyancy and propulsion systems of the DiverBot prototype and verify the implemented control software in actual operating conditions.

Figure 7.17: Eight thruster arrangement (top view).

7. Experimental Results

7.5.1 Depth and Heading Maneuvers

The aim of this experiment is to perform setpoint regulation tasks to observe the step response of depth and heading autopilots. Thus, a set of trials is performed combining depth and heading movements, as observed in Figure 7.18.

Due to the symmetries of the vehicle configuration, is possible to reduce the parameters of the PI controllers to two. Being $(K = 10)$, $(T_i = 12s)$ for translation controllers and $(K = 4)$, $(T_i = 4.8s)$ for rotation controllers, which is in accordance to the fact that drag effects are higher for depth translations than heading rotations. Such parameters are empirically determined increasing the proportional gain to obtain fast responses with small overshoots and oscillations, and then adding some integral action to eliminate steady-state errors.

The graphs on Figure 7.19 present the measured depth and heading and the corresponding thruster commands expressed over time. It can also be observed that the robot keeps on the surface when the autopilots are disabled which is convenient in case of power failure. The obtained results show an acceptable performance for both autopilots in terms of settling time with small oscillations around the desired values, making possible depth and heading control.

Figure 7.18: Snapshot sequence corresponding to depth control (upper) and heading control (lower). For trials in vehicle mode, the robot is trimmed to be slightly positively buoyant with horizontal attitude.

7.5 Underwater Maneuvers in Vehicle Mode

Figure 7.19: Time response of depth and heading autopilots, and commands for the respective thrusters during setpoint regulation tests. The coloured stripes point out a time period where autopilots have been disabled (t_3 , t_6 , t_7 , and t_8 are not used on this experiment).

7. Experimental Results

7.5.2 Autopilots and Manual Commands

An important feature of the proposed control scheme is the possibility to combine manual commands provided by a human operator with those computed by the depth and heading autopilots in order to perform complex tasks. The aim of this experiment is therefore to teleoperate the DiverBot prototype in order to pass under two crossbars installed in the water tank, as shown in Figure 7.20.

The graphs on Figure 7.21 present the measured depth and heading against desired values and the corresponding thruster commands expressed over time. The settling time for upward motion is shorter than the time required for downward movements due to positive buoyancy. Time values are estimated based on the average period measured on the robot controller which is around 40ms.

The manual commands are applied on the horizontal thrusters to displace the robot forward or backward once desired depth is attained. The control signals for these thrusters include the control actions calculated by the autopilots and those introduced by the operator. The obtained results show that DiverBot performs both forward and backward motion in less than 5 minutes without touching the obstacles, which would be difficult to achieve in open loop.

Figure 7.20: Underwater maneuvers consisting on displace DiverBot under the crossbars without contact them (forward motion). Setpoint and manual commands are applied by an operator using a joystick.

7.5 Underwater Maneuvers in Vehicle Mode

Figure 7.21: Time response of autopilots and commands for the respective thrusters during vehicle maneuvers. The coloured ellipses highlight the moments where manual commands are applied for (a) forward and (b) backward motion (t_3 and t_7 are disabled for this experiment).

7. Experimental Results

7.5.3 Position Keeping and Disturbances

Position-keeping is referred as the ability of a marine vehicle to keep a fixed position despite external disturbances acting over the system, which constitutes an important feature for any underwater vehicle. The aim of this experiment consists on testing the performance of the control system against external disturbances applied on the underwater robot, as described in Figure 7.22.

It is worth mentioning that the control scheme is also prepared to compensate for variations in roll and pitch angles. Nevertheless, these autopilots are not used for this application since the robot is fitted with low power thrusters which are not capable to overcome the restoring moments of the robot.

The graphs on Figure 7.23 present the measured depth and heading with respect to the setpoint values, and the corresponding thruster commands. The robot undergoes an arbitrary force applied on the robot torso using a stick in two different times. At these moments is possible to observe the system response through the control actions computed for vertical thrusters. In both cases DiverBot takes less than 50 seconds to recover the initial depth and heading values. Thus, the control strategy is robust against moderate external perturbations.

Figure 7.22: Snapshot sequence corresponding to depth and heading control for position keeping. An external force is applied on the system (upper) and then, DiverBot recovers the initial position (lower).

7.5 Underwater Maneuvers in Vehicle Mode

Figure 7.23: Time response of depth and heading autopilots, and commands for the respective thrusters during position keeping control. The underwater robot undergoes two external disturbances after 220s and 300s, respectively (t_3 , t_6 , t_7 , and t_8 are disabled for this experiment).

7. Experimental Results

7.5.4 Changes in Robot Configuration

In the previous experiments, hydraulic joints of DiverBot are kept at fixed positions to obtain a vehicle configuration during maneuvers. The objective of this experiment is to test the control system performance against disturbances produced by changes in the robot configuration as described in Figure 7.24.

The center of gravity position changes when the underwater robot moves its hydraulic arms and legs. This produces variations in the geometric model of the robot which no longer represent the actual situation of the system. On the other hand, inertial sensors are calibrated with respect to a conventional vehicle configuration, thus, small variations occur in computed orientations when DiverBot moves his arms and legs that would affect control system response.

Nevertheless, the graphs on Figure 7.25 show constant depth and heading responses with small oscillations around the desired values. The obtained results indicates that the autopilots maintain the underwater robot around the desired values of depth and heading despite of inaccuracies in the parameters. Thus, the control strategy is robust against changes in robot configuration.

Figure 7.24: Snapshot sequence corresponding to position keeping control while DiverBot modifies the position of arms and legs. The autopilots are required to keep the robot at $0.5m$ depth and 0° heading.

7.5 Underwater Maneuvers in Vehicle Mode

Figure 7.25: Time evolution of depth and heading parameters against desired values, along with the corresponding control signals for electric thrusters during position keeping control with changes in robot configuration (t_3 , t_6 , t_7 , and t_8 are not used on this experiment).

7.6 Discussion

Along this chapter several experiments concerning the performance of the underwater anthropoid robot under both functional modes are presented.

According to the obtained results, the developed prototype can move its limbs using all the joints simultaneously to execute stable underwater motion and reproduce walking sequences requiring some unstable movements. Thus, the elements defined in Chapter 5 for the stability analysis are according to the actual behaviour of DiverBot, and the hydraulic servo-control provides acceptable responses.

Also, the underwater robot is capable to perform maneuvers in vehicle mode involving depth and surge translations, heading rotations, and requiring the use of autopilots combined with manual commands introduced by the operator. Thus, the control strategy described in Chapter 6 meet the initial requirements.

In general terms, the correct execution of these trials reflect the fact that the hardware and software parts of DiverBot (presented in Chapters 3 and 4, respectively) have been correctly developed, allowing the use of the robot in underwater conditions. Accordingly, the selected sensors and actuators are well dimensioned as they are capable to execute the expected underwater tasks.

The experiments allow to validate the robot performance and explore the limits of the prototype to propose improvements and further experiments. For instance, using a hydraulic station with higher power allow to increase the flow provided to the robot producing faster movements. In the similar manner, replacing the thrusters with higher power ones could provide higher velocities, or even allow the use of thrusters to compensate movements in anthropoid mode.

In the previous experiments, stable movements are achieved through pre-calculated trajectories. However, it could be interesting to test the robot against online motion commands, *e.g.*, in underwater manipulation tasks. These experiments can be carried out using a master device that allows whole-body teleoperation instead of one or more joysticks, taking advantage of the kinematic similarities between the human operator and the slave system.

*One never notices what has been done;
one can only see what remains to be done.*

Marie Curie

Chapter 8

Conclusions

This thesis has focused on the research and development of a novel underwater humanoid robot intended to perform remotely controlled operations in underwater environments. The robot was realized with anthropoid proportions to provide an intuitive structure for teleoperation, and the particular capability to transform into a remotely operated vehicle for large displacements through the water. As presented in Chapter 2, humanoid robots for underwater operations are scarce and most of the related works refers to conceptual ideas not yet realized.

Thus, the design and control of a robotic diver for underwater operation powered by hydraulic and electric actuators is not a trivial task, and constitutes a challenge per se, where several topics must be addressed and multiple subsystems must be developed, involving several complex and time consuming tasks.

The interest of developing a functional prototype is to provide a proof of concept of the idea that robotic divers can be used for dangerous underwater works which are nowadays performed by human divers, assuming the risks involved in such activities. Hence, the developed robot constitutes a step towards the next generation of machines for underwater works in hostile environments, such as offshore platforms, sewage plants, or nuclear power reactors.

8. Conclusions

Several aspects concerning the design and control of the underwater anthropoid robot have been addressed along this thesis. Two chapters have been focused on design aspects, dealing with the hardware and software parts of the robot. Another two chapters have been developed around control aspects for underwater locomotion and setpoint regulation tasks. Finally, the performance of the developed prototype together with the developed control strategies have been validated through a series of experiments carried out in actual operating conditions.

Chapter 3 presented the design and fabrication of the hardware part of the underwater anthropoid robot. Depending on the task, the robotic diver can be configured under two functional modes *i.e.*, anthropoid and vehicle mode. The hardware design approach was centred in partitioning the system into several modules or subsystems for developing specific functions. Being, the modules conforming the body of the robot (*i.e.*, torso, legs, arms and hands, head, propulsion and ballast systems), and the underwater control unit charged to control all sensor and actuators of the robot. The integration of these subsystems resulted in the DiverBot prototype, presented at the end of the chapter.

Chapter 4 covered the design and implementation of the software part of the underwater anthropoid robot. As a first step, software requirements were identified to determine the main functions of the system through UML diagrams. The system requirements were arranged into functional blocks relating sensors and actuators according to the process performed by the robot. Then, a LabVIEW implementation was carried out to provide the corresponding functions. All these functions were integrated into a user interface which allows an operator to manage all the sensors and actuators of DiverBot from a control station. Besides, a master device or joystick was integrated to facilitate robot teleoperation.

Chapter 5 dealt with statically stable locomotion in underwater environments. For knuckle-walking motion, the margin of static stability was computed through a screw-theory method as a distance depending on contact points and external forces applied to the robot. Therefore, a position analysis was carried out to calculate the contact points between robot and ground. A method based on virtual chains was applied for center of gravity calculation, and extended to compute the center of buoyancy. A kinematics simulator was realized to calculate walking sequences

and determine if they are stable before being executed by position controllers integrated in the software system of DiverBot.

Chapter 6 put forward a geometry-based control for setpoint regulation tasks under vehicle configuration. Expressions for calculation of position and attitude errors were derived using suitable representations. The navigational instruments providing feedback signals were described. A propulsion map was derived from the screw coordinates of the vehicle and used to allocate thruster control errors in an optimal manner depending on the position and orientation error of the vehicle. Depth and heading autopilots were implemented using optimal allocation together with linear controllers. The control scheme was implemented as part of the software system of DiverBot to evaluate its performance.

Chapter 7 presented experimental results concerning the performance of the robotic diver under both functional modes. The obtained results have shown that the developed prototype is capable to walk under water using its four limbs. The simulation results coincides with the actual response of DiverBot and the joint controllers provides acceptable responses. Furthermore, depth and heading control was validated in vehicle mode since the robot accomplishes different maneuvers involving autopilots combined with manual commands. Accordingly, the hardware and software systems of DiverBot were correctly developed, otherwise the experiments would not been possible in underwater conditions.

8.1 Future Work

The design and control of a robotic diver constitutes a first step towards future applications of humanoid robots in dangerous underwater activities, but there is a lot of pending work to improve the performance and usability of such robots.

In this regard, the prototype developed in this thesis together with the proposed control schemes provides a starting point for further research.

Multiple improvements can be suggested for the underwater anthropoid robot (*e.g.*, adding more degrees of freedom to improve dexterity, including force sensors to have haptic feedback, or implementing stereo vision systems), and several future projects could bring added value to the system for performing underwater works; some of them are introduced in the following paragraphs.

8. Conclusions

Whole-Body Teleoperation

As described in Section 4.6.4, the software system of DiverBot integrates a joystick to move along the user interface and send commands to the robot *e.g.*, move specific joints, adjust camera zoom, or accelerate thrusters. When the complexity of the task increases the use of other devices could be advantageous. Thus, the operator is allowed to select between joystick or an external master device.

A master device prepared to capture kinematic motion of the operator could be a valuable tool to control the robotic diver for tasks requiring on-the-fly robot teleoperation, such as bimanual telemanipulation. Among recent technologies, vision-based systems and motion capture systems are widely used to study human-robot interaction. For instance, an IMU-based motion capture system is applied for teleoperation of the NASA Robonaut in (Miller et al., 2004).

Hence, the implementation of a master device for whole-body teleoperation constitutes an interesting future project for the accomplishment of complex tasks, taking advantage of the kinematic similarity between human pilot and robot, and providing greater accessibility for non-technical operators.

Variable Ballast System

The underwater robot is fitted with a modular ballast system described in Section 3.3.2, which is manually adjusted to be negatively buoyant for anthropoid mode tasks and close to neutral buoyancy when in vehicle mode. Therefore, a remarkable improvement consists on the implementation of a variable ballast system (VBS) in order to control the buoyancy of DiverBot automatically.

Most VBS consist on a pressure vessel and a high pressure pump to adjust the weight of the vehicle by charging or discharging seawater into the pressure tank *e.g.*, (Qiu, 2008). Variable ballasts are commonly used on hybrid underwater vehicles which are operated at neutral buoyancy for some tasks and then are requested to sink for operations on the seafloor. It also allows the vehicle to adjust depth and become heavier in the presence of water currents.

The interest of implementing a VBS lies on the possibility to use DiverBot in both anthropoid and vehicle modes without need to put it on surface for trimming the ballast system. Besides, the ballast system could be adjusted to have the

center of gravity and center of buoyancy on the same position in order to eliminate righting moments and improve robot maneuverability.

Perception Capabilities

Despite the robot head is fitted with exteroceptive sensors *i.e.*, dome camera and sonar, DiverBot is treated as a teleoperated system along this thesis thus concentrating all perception and decision capabilities into the human operator.

Nevertheless, it results important to give greater autonomy to the robot in order to have a semi-autonomous system in which a number of low-level tasks are automated, allowing the operator to focus on critical aspects of the mission.

Computer vision algorithms can be implemented *e.g.*, to release the pilot to control the dome camera during a telemanipulation task. The camera can be programmed to track one or both hands automatically. Thus, the operator concentrates on the manipulation task and does not need to worry about adjusting the camera position while the robot arms are moving.

When light conditions are poor, acoustic sensors are preferred over optical ones. An imaging sonar can be used for obstacle avoidance or robot positioning with respect to submerged structures. Acoustic sensors are used together with cameras and other technologies on several applications.

For instance, an algorithm to fuse the data provided by a video camera and a scanning profiler sonar mounted on an ROV is proposed in (Barat and Rendas, 2005), while a laser emitter is used together with a camera for semi-autonomous grasping of unknown objects in (Prats et al., 2012).

Parallel Current Meter

Among the perception capabilities of an underwater robot, the measurement of external forces produced by water currents constitutes an important feature to improve the system response to external disturbances.

For this purpose, a novel device designed to measure the direction and speed of water currents is presented in Section 3.3.3, based on the pressure drag exerted by the fluid over a rigid sphere attached to a parallel orientation mechanism.

8. Conclusions

Hence, the implementation of the parallel current meter along with the experimental validation through hydrodynamic tests could be a starting point to develop advanced control strategies based on dynamic models that are capable to compensate for external disturbances produced by water currents.

On the other hand, the stability analysis presented in Chapter 5 can be extended to account for external perturbations. Once the current meter is working properly, it becomes straightforward to include the external forces due to water currents into the total destabilizing wrench of the system.

In the similar manner, the screw-based method can be extended to include any external force applied on the underwater robot *e.g.*, external perturbations produced by the umbilical cable could be considered in the stability analysis by adding a force sensor between umbilical and robot torso.

Hybrid Control Strategies

Along this thesis, the functional modes of DiverBot have been treated by separate. Robot locomotion is performed using only hydraulic joints with thrusters turned off and, on the contrary, vehicle maneuvers are realized using only thrusters with fixed joints. Indeed, the situation where joints are moved during a vehicle configuration is analysed as a control disturbance in Section 7.5.4.

Nevertheless, the proposed control strategies can be combined with a supervisory control scheme to allow the use of joints and thrusters simultaneously in hybrid configurations of the underwater robot. For instance, using thrusters to compensate external disturbances during quadrupedal locomotion, or using joints to grasp an object while keeping a floating position in vehicle mode.

To accomplish these tasks it could be necessary to increase the power available on the propulsion system along with the implementation of a variable ballast system. At higher velocities the hydrodynamic effects become significant and could be interesting to analyse its influence over the system.

Appendix A

Publications

The contributions of this thesis along with others activities developed during the PhD program had led to the following scientific publications, including JCR journals, patents, book chapters, and press articles.

Journals

- J. Serracín, L. Puglisi, R. Saltaren, G. Ejarque, J. Sabater-Navarro, and R. Aracil. *Kinematic analysis of a novel 2-DOF orientation device*. Robotics and Autonomous Systems, Elsevier, Vol. 60, Issue 6, Jun 2012, pp. 852-861.
- M. Urdaneta, C. García, G. Poletti, G. Ejarque, R. Saltaren, and R. Aracil. *Development of a novel autonomous robot for navigation and inspect in oil wells*. Journal of Control Engineering and Applied Informatics, CEAI, Vol. 14, Issue 3, Sep 2012, pp. 9-14.

At the moment of writing this document, the following document is under review process in a JCR journal:

A. Publications

- R. Saltaren, G. Ejarque, L. Puglisi, C. García, and R. Aracil. *An Underwater Humanoid Robot for Works on Seabed: Design, Development and Practical Results*. IEEE/ASME Transactions on Mechatronics. Regular paper. Manuscript ID: TMECH-03-2016-5260.

Patents

- G. Ejarque, R. Saltaren, G. Poletti, and R. Aracil. *Robot submarino humanoide transformable*. Patent No. ES-2544007-B2, Universidad Politécnica de Madrid, Spanish Patents and Trademarks Office, Feb 2016.
- R. Saltaren, R. Aracil, C. García, L. Puglisi, and G. Ejarque. *Mecanismo del tipo articulado de morfología serial-paralela de cuatro grados de libertad para apuntar y guiar dispositivos hacia dianas distales*. Patent No. ES-2538415-B2, Universidad Politécnica de Madrid, Spanish Patents and Trademarks Office, Nov 2015.
- G. Ejarque, R. Saltaren, G. Poletti, and R. Aracil. *Dispositivo y método para la medición de corrientes de fluidos mediante mecanismo paralelo esférico actuado por fuerzas de arrastre*. Patent No. ES-2525394-B2, Universidad Politécnica de Madrid, Spanish Patents and Trademarks Office, Jul 2015.
- G. Ejarque, R. Saltaren, G. Poletti, and R. Aracil. *Robot submarino modular*. Patent No. ES-2525773-B2, Universidad Politécnica de Madrid, Spanish Patents and Trademarks Office, Apr 2015.

At the moment of writing this document, the following document is under evaluation process:

- G. Poletti, R. Saltaren, G. Ejarque, and R. Aracil. *Sistema vestibular para interacción con entornos remotos mediante información gestual y sensaciones táctiles y procedimiento de uso*. Patent Application No. ES-2532132-A1, UPM, Spanish Patents and Trademarks Office, Mar 2015.

Book Chapters

- G. Ejarque, R. Saltaren, R. Aracil, G. Poletti, and C. García. *Humanoid robots for underwater works*. RoboCity16: Open conference on future trends in robotics, RoboCity2030. Centre for Automation and Robotics (CSIC-UPM), ISBN: 978-84-608-8452-1, pp. 177-186, May 2016.
- G. Poletti, G. Ejarque, C. García, R. Saltaren, R. Aracil, and M. Urdaneta. *Autonomous robot for navigation and inspection in oil wells*. Robótica Cognitiva, Robocity 2030. Universidad Nacional de Educación a Distancia (UNED), ISBN: 978-84-695-8175-9, pp. 93-107, Jul 2013.
- H. Moreno, L. Puglisi, R. Saltaren, C. Alvarez, C. Peña, C. Perez, and G. Ejarque. *Avances en el control del robot submarino Remo I*. Robots de Exteriores, Robocity 2030. Consejo Superior de Investigaciones Científicas (CSIC), ISBN: 978-84-614-5558-4, pp. 301-320, Dic 2010.

Press and Media

- *Un transformer con el sello UPM para explorar los oceanos*. Revista Universidad Politécnica de Madrid, No. 30, Apr 2015, (http://www.upm.es/sfs/Rectorado/GabinetedelRector/RevistaUPM/NUMERO_30_VER.pdf), pp. 4-6. ISSN: 1699-8162.
- *Carlitos, un transformer submarinista*. Boletín In-On ETSII, Universidad Politécnica de Madrid, Apr 2015. Retrieved: http://www.etsii.upm.es/saladeprensa/newsletters/201504_2/Boletin_INON_2015_04_29.html. Accessed: Feb 2016.

A. Publications

Appendix B

Kinematic Equations

The following sections present some useful equations for kinematics calculation purposes. Section B.1 presents the equations used to calculate specific parameters of the robot geometry. The closed-form solution of a particular transcendental equation is derived in Section B.2. Finally, Section B.3 depicts a rotation matrix related to a general spherical displacement using quaternions.

B.1 Robot Torso Geometry

DiverBot presents two symmetric and collinear rotational joints V used during transformation between vehicle and anthropoid modes (Sections 3.2.1 and 3.2.2).

For quadrupedal locomotion, both joints are maintained at a constant angular position $\beta = \pi/4$ which allows for adequate mobility according to the prototype dimensions and joint ranges (see Figure B.1), while for displacements in vehicle mode angle $\beta = 0$ in order to reach a compact ROV-like configuration.

Thus, a virtual link is defined by the shortest distance ℓ_t from the axis of rotational joint H to that of joint R. Hence, parameter ℓ_t takes different values depending on the current robot configuration.

B. Kinematic Equations

Figure B.1: Scheme for robot torso geometry.

The following equations illustrate the procedure for ℓ_t calculation, as well as for two angles depending on β , used for calculations on Chapters 5 and 6.

From the geometry of Figure B.1, the following angles are defined

$$\sigma_1 = \text{atan}(d_1/d_2), \quad \sigma_3 = \pi - \sigma_1, \quad (\text{B.1})$$

$$\sigma_2 = \text{atan}(d_4/d_3), \quad \sigma_4 = \beta - \sigma_2. \quad (\text{B.2})$$

Depending on $\gamma' = \sigma_3 + \sigma_4$, two variables are calculated as follows

$$\gamma = \begin{cases} \gamma' & ; (\gamma' \leq \pi), \\ 2\pi - \gamma' & ; (\gamma' > \pi), \end{cases} \quad \mu = \begin{cases} +1 & ; (\gamma' \leq \pi), \\ -1 & ; (\gamma' > \pi), \end{cases} \quad (\text{B.3})$$

and the sides of triangle defined by joints H, V, and R are calculated as

$$\ell_t = +\sqrt{\ell_{12}^2 + \ell_{34}^2 - 2\ell_{12}\ell_{34}\cos(\gamma)}. \quad (\text{B.4})$$

where

$$\ell_{12} = +\sqrt{d_1^2 + d_2^2}, \quad \ell_{34} = +\sqrt{d_3^2 + d_4^2}, \quad (\text{B.5})$$

As observed in Figure B.1, angle β_t can be calculated by

$$\beta_t = \pi/2 - \mu\sigma_5 - \sigma_6, \quad (\text{B.6})$$

B.1 Robot Torso Geometry

Table B.1: Torso geometry parameters.

length	d_1	d_2	d_3	d_4
(mm)	140	85	711.5	281.5

where

$$\sigma_5 = \text{atan2} \left(\frac{\ell_{34} \sin(\gamma)}{\ell_t}, \frac{\ell_{12}^2 + \ell_t^2 - \ell_{34}^2}{2\ell_{12}\ell_{34}} \right), \quad (\text{B.7})$$

$$\sigma_6 = \text{atan}(d_2/d_1). \quad (\text{B.8})$$

The elements of atan2 corresponds to the results obtained from the law of sines and cosines, respectively. In a similar fashion, angle β_R can be expressed as

$$\beta_R = \pi/2 - \sigma_7 - \mu\sigma_8, \quad (\text{B.9})$$

where

$$\sigma_7 = \text{atan2} \left(\frac{d_3}{\ell_{34}}, \frac{d_4^2 + \ell_{34}^2 - d_3^2}{2\ell_{34}d_4} \right), \quad (\text{B.10})$$

$$\sigma_8 = \text{atan2} \left(\frac{\ell_{12} \sin(\sigma_5)}{\ell_{34}}, \frac{\ell_{34}^2 + \ell_t^2 - \ell_{12}^2}{2\ell_{34}\ell_t} \right). \quad (\text{B.11})$$

Solving equations (B.4), (B.6), and (B.9) for the geometric parameters listed in Table B.1, and a fixed angular position $\beta = \pi/4$, yields

$$\ell_t = 903.8 \text{ mm}, \quad (\text{B.12})$$

$$\beta_t = 0.5136 \text{ rad}, \quad \beta_R = 0.2718 \text{ rad}, \quad (\text{B.13})$$

while the values obtained for $\beta = 0$ are

$$\ell_t = 809.0 \text{ mm}, \quad (\text{B.14})$$

$$\beta_t = 6.1074 \text{ rad}, \quad \beta_R = 0.1758 \text{ rad}. \quad (\text{B.15})$$

B. Kinematic Equations

B.2 Transcendental Equation

Any equation of the form

$$a \cos(\vartheta) + b \sin(\vartheta) = c, \quad (\text{B.16})$$

can be solved for ϑ by introducing two variables r and ρ , such that

$$a = r \cos(\rho), \quad b = r \sin(\rho), \quad (\text{B.17})$$

and

$$r = \sqrt{a^2 + b^2}, \quad \rho = \text{atan2}(b, a). \quad (\text{B.18})$$

Substituting (B.17) in (B.16) yields

$$\cos(\rho) \cos(\vartheta) + \sin(\rho) \sin(\vartheta) = \frac{c}{r}. \quad (\text{B.19})$$

Applying the angle addition formula gives

$$\cos(\rho - \vartheta) = \frac{c}{r}, \quad (\text{B.20})$$

and the Pythagorean trigonometric identity

$$\sin(\rho - \vartheta) = \pm \sqrt{1 - \cos(\rho - \vartheta)^2} = \frac{\pm \sqrt{a^2 + b^2 - c^2}}{r}. \quad (\text{B.21})$$

Hence, ϑ is determined by using atan2 function

$$\vartheta = \rho \pm \text{atan2} \left(+\sqrt{a^2 + b^2 - c^2}, c \right), \quad (\text{B.22})$$

Replacing (B.18) into (B.22) yields

$$\vartheta = \text{atan2}(b, a) + \varepsilon \text{atan2} \left(+\sqrt{a^2 + b^2 - c^2}, c \right), \quad (\text{B.23})$$

where $\varepsilon = \pm 1$ is an independent parameter which allows to chose between elbow-up and elbow-down configurations. Equation (B.23) is a widely used formula for inverse kinematic calculations *e.g.*, (Craig, 2005).

B.3 Rodrigues' Rotation Formula

Euler's theorem states that any displacement of a rigid body which maintains a fixed point, equals to a rotation around a line passing through the point.

Let consider a vector $\mathbf{r}_1$ rotate an angle θ about an axis through the origin O , represented by the unit vector $\hat{\mathbf{n}} \in \mathbb{R}^3$ as depicted in Figure B.2.

Figure B.2: Vector diagram of a spherical displacement.

A rotation matrix $R \in SO(3)$ is used to transform the position vector $\mathbf{r}_1$ into $\mathbf{r}_2$. The component of $\mathbf{r}_1$ which is parallel to $\hat{\mathbf{n}}$, named $\mathbf{r}_{\parallel}$, will not change during the rotation. The component of $\mathbf{r}_1$ which is perpendicular to $\hat{\mathbf{n}}$, named $\mathbf{r}_{\perp}$, will rotate about the axis in the plane normal to the axis of rotation. From the geometry of Figure B.2 the transformation can be expressed as

$$\begin{aligned} \mathbf{r}_2 &= \mathbf{r}_{\parallel} + \mathbf{r}_{\perp} = R \mathbf{r}_1, \\ \mathbf{r}_2 &= \underbrace{\mathbf{r}_1 + \hat{\mathbf{n}} \times (\hat{\mathbf{n}} \times \mathbf{r}_1)}_{\mathbf{r}_{\parallel}} + \underbrace{c\theta(-\hat{\mathbf{n}} \times (\hat{\mathbf{n}} \times \mathbf{r}_1)) + s\theta(\hat{\mathbf{n}} \times \mathbf{r}_1)}_{\mathbf{r}_{\perp}} = R \mathbf{r}_1, \\ \mathbf{r}_2 &= \mathbf{r}_1 + s\theta(\hat{\mathbf{n}} \times \mathbf{r}_1) + (1 - c\theta)(\hat{\mathbf{n}} \times (\hat{\mathbf{n}} \times \mathbf{r}_1)) = R \mathbf{r}_1. \end{aligned} \quad (\text{B.24})$$

where $c\theta$ is a shorthand notation for $\cos(\theta)$ and $s\theta$ for $\sin(\theta)$.

A square matrix $S \in \mathbb{R}^{3 \times 3}$ is skew-symmetric when satisfies the condition ($S^T = -S$). Hence the skew-symmetric matrix S represents the linear transformation that computes the cross product of vector $\hat{\mathbf{n}}$ with any other vector in $\mathbb{R}^3$

B. Kinematic Equations

such that

$$S(\hat{\mathbf{n}}) = [\hat{\mathbf{n}} \times] = \begin{bmatrix} 0 & -n_z & n_y \\ n_z & 0 & -n_x \\ -n_y & n_x & 0 \end{bmatrix}, \quad (\text{B.25})$$

Substituting Equation (B.25) into Equation (B.24) yields

$$\mathbf{r}_2 = [I_{3 \times 3} + (s\theta)S(\hat{\mathbf{n}}) + (1 - c\theta)S^2(\hat{\mathbf{n}})] \mathbf{r}_1, \quad (\text{B.26})$$

hence

$$R = I_{3 \times 3} + (s\theta)S(\hat{\mathbf{n}}) + (1 - c\theta)S^2(\hat{\mathbf{n}}). \quad (\text{B.27})$$

Equation (B.27) is known as Rodrigues' formula for a spherical displacement of a rigid body (Rodrigues, 1840). Matrix R can be seen as an axis-angle representation of the orientation of a rigid body in three dimensional Euclidean space.

Let define $q \in \mathbb{S}^3$ as a unit quaternion of the form

$$q = [q_0 \quad q_1 \quad q_2 \quad q_3]^T, \quad (\text{B.28})$$

where

$$q_0 = c(\theta/2), \quad (\text{B.29})$$

$$\mathbf{q} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \hat{\mathbf{n}} s(\theta/2), \Rightarrow \hat{\mathbf{n}} = \frac{\mathbf{q}}{s(\theta/2)}. \quad (\text{B.30})$$

This representation uses four parameters *i.e.*, three associated with the direction of the rotation axis $\hat{\mathbf{n}}$ and one associated with the angle of rotation θ . However, only two of the three parameters associated with the direction of the rotation axis are independent since they must satisfy the condition

$$\hat{\mathbf{n}}^T \hat{\mathbf{n}} = 1. \quad (\text{B.31})$$

Applying the skew-symmetric transformation to the unit vector $\hat{\mathbf{n}}$ gives

$$S(\hat{\mathbf{n}}) = \frac{1}{s(\theta/2)} S(\mathbf{q}). \quad (\text{B.32})$$

B.3 Rodrigues' Rotation Formula

The following expressions are obtained from the double-angle and half-angle formulas, respectively

$$s\theta = 2s(\theta/2)c(\theta/2), \quad (1 - c\theta) = 2s^2(\theta/2). \quad (\text{B.33})$$

The results in (B.32) and (B.33) are inserted into (B.27) to obtain

$$R(q) = I_{3 \times 3} + 2q_0 S(\mathbf{q}) + 2S^2(\mathbf{q}), \quad (\text{B.34})$$

which is the Rodrigues' formula expressed in terms of unit quaternions. The obtained equation can be expressed in matrix form as

$$R(q) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} + 2q_0 \begin{bmatrix} 0 & -q_3 & q_2 \\ q_3 & 0 & -q_1 \\ -q_2 & q_1 & 0 \end{bmatrix} - 2 \begin{bmatrix} q_2^2 + q_3^2 & -q_1 q_2 & -q_1 q_3 \\ -q_1 q_2 & q_1^2 + q_3^2 & -q_2 q_3 \\ -q_1 q_3 & -q_2 q_3 & q_1^2 + q_2^2 \end{bmatrix},$$

hence

$$R(q) = \begin{bmatrix} 1 - 2(q_2^2 + q_3^2) & 2(q_1 q_2 - q_3 q_0) & 2(q_1 q_3 + q_2 q_0) \\ 2(q_1 q_2 + q_3 q_0) & 1 - 2(q_1^2 + q_3^2) & 2(q_2 q_3 - q_1 q_0) \\ 2(q_1 q_3 - q_2 q_0) & 2(q_2 q_3 + q_1 q_0) & 1 - 2(q_1^2 + q_2^2) \end{bmatrix}. \quad (\text{B.35})$$

B. Kinematic Equations

Appendix C

Screw Theory Concepts

Screw theory was first developed by *Sir Robert Ball* on the nineteenth century for application in rigid body mechanics and nowadays constitutes an important tool in robot mechanics. Screws are six-dimensional vectors comprising a pair of three-dimensional vectors. Along this research, some methods of the screw theory are applied in Chapters 5 and 6. Basic concepts about the fundamental elements of screw theory are given in the following sections. Further reading on this topic can be found in (Tsai, 1999) and (Davidson and Hunt, 2004).

C.1 Screw Coordinates of a Wrench

Any system of n forces and m couples acting on a rigid body can be reduced to a resultant force $\mathbf{f}$ and a resultant couple $\mathbf{c}$ such that

$$\mathbf{f} = \sum_{i=1}^n \mathbf{f}_i, \quad \mathbf{c} = \sum_{i=1}^n (\mathbf{p}_i \times \mathbf{f}_i) + \sum_{i=1}^m \mathbf{c}_i, \quad (\text{C.1})$$

where $\mathbf{p}_i$ is the position vector of $\mathbf{f}_i$. In most of cases the resultant force and the couple are not collinear (Tsai, 1999).

C. Screw Theory Concepts

Theorem C.1.1 (Poinsot's theorem). *Any system of forces and couples acting on a rigid body is equivalent to a resultant force along an axis plus a couple which is parallel to that axis.*

According to Theorem C.1.1, there exists a unique axis where the resultant force $\mathbf{f}$ and a resultant couple $\mathbf{c}_{\parallel}$ are collinear. That unique axis corresponds to the axis of a screw $\$ \in \mathbb{R}^6$ which combined with a scalar magnitude defines a wrench $\$'$ (Ball, 1900). The coordinates of a screw can be represented by a pair of vectors in three-dimensional Euclidean space (Tsai, 1999)

$$\$ = \begin{bmatrix} \hat{\mathbf{s}} \\ \mathbf{r} \times \hat{\mathbf{s}} + h\hat{\mathbf{s}} \end{bmatrix}, \quad (\text{C.2})$$

where $\hat{\mathbf{s}} \in \mathbb{R}^3$ is a unit vector directed along the screw axis, $\mathbf{r} \in \mathbb{R}^3$ is a position vector of one point on the screw axis, and $h \in \mathbb{R}$ is the pitch of screw $\$$.

It can be shown that the components of a wrench $\$'$ are obtained as of the resultant force $\mathbf{f}$ and couple $\mathbf{c}$ as

$$\hat{\mathbf{s}} = \frac{\mathbf{f}}{\|\mathbf{f}\|}, \quad \mathbf{r} = \frac{\mathbf{f} \times \mathbf{c}}{\mathbf{f}^T \mathbf{f}}, \quad h = \frac{\mathbf{f}^T \mathbf{c}}{\mathbf{f}^T \mathbf{f}}. \quad (\text{C.3})$$

Thus, the system of forces and couples acting on a rigid body can be thought as a wrench acting on a screw with scalar intensity $f = \|\mathbf{f}\|$

$$\$' = f \begin{bmatrix} \hat{\mathbf{s}} \\ \mathbf{r} \times \hat{\mathbf{s}} + h\hat{\mathbf{s}} \end{bmatrix} = \begin{bmatrix} \mathbf{f} \\ \mathbf{c} \end{bmatrix}, \quad (\text{C.4})$$

where the first three components of $\$' \in \mathbb{R}^6$ represent the resultant force and the last three components correspond to the resultant couple

$$\mathbf{f} = f\hat{\mathbf{s}}, \quad \mathbf{c} = \underbrace{(\mathbf{r} \times \mathbf{f})}_{\mathbf{c}_{\perp}} + \underbrace{(h\mathbf{f})}_{\mathbf{c}_{\parallel}}. \quad (\text{C.5})$$

Hence, a zero pitch wrench ($h = 0$) represents a pure force acting on a line of action *i.e.*, screw axis, while an infinite pitch wrench ($h = \infty$) corresponds to a pure couple acting on the rigid body (Davidson and Hunt, 2004).

C.2 Screw Coordinates of a Twist

Consider a set of n angular velocity vectors and m translational velocity vectors instantaneously applied on the rotational and prismatic joints of a general serial kinematic chain, respectively. These velocities can be reduced to a resultant angular and translational velocity vectors, such that

$$\mathbf{w} = \sum_{i=1}^n \mathbf{w}_i, \quad \mathbf{v} = \sum_{i=1}^n (\mathbf{p}_i \times \mathbf{w}_i) + \sum_{i=1}^m \mathbf{v}_i, \quad (\text{C.6})$$

where $\mathbf{p}_i$ is the position vector of $\mathbf{w}_i$. In most of cases the resultant angular $\mathbf{w}$ and translational $\mathbf{v}$ velocities are not collinear.

Theorem C.2.1 (Chasles's theorem). *A general displacement of a rigid body from one location to another can be produced by a rotation about an axis combined with a translation parallel to that axis.*

According to Theorem C.2.1, there exists a unique axis where the resultant angular velocity $\mathbf{w}$ and a resultant linear velocity $\mathbf{v}_{\parallel}$ are collinear. That unique axis corresponds to the axis of a screw $\$ \in \mathbb{R}^6$ which combined with a scalar magnitude defines a twist $\$$ (Ball, 1900). The coordinates of a screw can be represented by a pair of vectors in Euclidean space (Tsai, 1999)

$$\$ = \begin{bmatrix} \hat{\mathbf{s}} \\ \mathbf{r} \times \hat{\mathbf{s}} + h\hat{\mathbf{s}} \end{bmatrix}, \quad (\text{C.7})$$

where $\hat{\mathbf{s}} \in \mathbb{R}^3$ is a unit vector directed along the screw axis, $\mathbf{r} \in \mathbb{R}^3$ is a position vector of one point on the screw axis, and $h \in \mathbb{R}$ is the pitch of screw $\$$.

It can be shown that the components of a twist $\$$ are obtained as of the resultant angular velocity $\mathbf{w}$ and translational velocity $\mathbf{v}$ as

$$\hat{\mathbf{s}} = \frac{\mathbf{w}}{\|\mathbf{w}\|}, \quad \mathbf{r} = \frac{\mathbf{w} \times \mathbf{v}}{\mathbf{w}^T \mathbf{w}}, \quad h = \frac{\mathbf{w}^T \mathbf{v}}{\mathbf{w}^T \mathbf{w}}. \quad (\text{C.8})$$

Hence, the linear and angular velocities applied on a serial kinematic chain can

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be thought as a twist acting on a screw with scalar amplitude $w = \|\mathbf{w}\|$

$$\mathbb{S} = w \begin{bmatrix} \hat{\mathbf{s}} \\ \mathbf{r} \times \hat{\mathbf{s}} + h\hat{\mathbf{s}} \end{bmatrix} = \begin{bmatrix} \mathbf{w} \\ \mathbf{v} \end{bmatrix}, \quad (\text{C.9})$$

where the first three components of $\mathbb{S} \in \mathbb{R}^6$ represent the resultant angular velocity and the last three components correspond to the resultant linear velocity

$$\mathbf{w} = w\hat{\mathbf{s}}, \quad \mathbf{v} = \underbrace{(\mathbf{r} \times \mathbf{w})}_{\mathbf{v}_\perp} + \underbrace{(h\mathbf{w})}_{\mathbf{v}_\parallel}. \quad (\text{C.10})$$

A zero pitch twist ($h = 0$) represents pure rotational motion of a rigid body, while an infinite pitch twist ($h = \infty$) corresponds to pure translational motion of a rigid body (Davidson and Hunt, 2004).

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