UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingenieros Industriales

Design and Development of Self-Configurable Modular Robotic Systems for Mining Operations

D O C T O R A L T H E S I S

Submitted for the degree of Doctor by:

Virgilio Augusto Gomez Lambo
Master in Mechatronic Engineering

Madrid, 2024

UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingenieros Industriales

Doctoral Degree in Automatic Control and Robotics

Design and Development of Self-Configurable Modular Robotic Systems for Mining Operations

D O C T O R A L T H E S I S

Submitted for the degree of Doctor by:

Virgilio Augusto Gomez Lambo
Master in Mechatronic Engineering

Under the supervision of:
Dr. Miguel Hernando Gutierrez (Supervisor)
Dr. Claudio Rossi (Co-supervisor)

Madrid, 2024

Title: Design and Development of Self-Configurable Modular Robotic Systems for Mining Operations

Author: Virgilio Augusto Gomez Lambo

Doctoral Programme: Automatic Control and Robotics

Thesis Supervision:

Dr. Miguel Hernando Gutierrez, Tenured University Professor, Universidad Politécnica de Madrid (Supervisor)

Dr. Claudio Rossi, Full Professor, Universidad Politécnica de Madrid (Co-supervisor)

External Reviewers:

Thesis Defense Committee:

Thesis Defense Date:

This thesis has been partially supported by the European Commission's Horizon 2020 research and innovation program (ROBOMINERS, grant no. 820971).

A mi amor, Cristina,
A mis padres, Oswaldo y María Luisa,
A mis hermanos, Oswaldo y Francisco,
Al resto de mi família,
A todos mis amigos,
Y a todos los que se atreven
a emprender este camino sin miedo

Acknowledgement

First and foremost, I would like to express my deepest gratitude to my supervisors, Professors Miguel Hernando Gutierrez and Claudio Rossi. Your guidance, clarity, and perspective at every step of this journey have been instrumental in shaping the professional I have become. Miguel, I am profoundly grateful for your constant encouragement and invaluable advice that pushed me to achieve my goals. Claudio, I sincerely appreciate your financial and strategic backing, as well as the opportunity to participate in the ROBOMINERS project. This experience has significantly contributed to my growth as a student, researcher, and academic over the years.

I would also like to express my heartfelt thanks to the entire staff at the TalTech Biorobotics Lab for their warm welcome during my research stay in Tallinn. Special thanks to Prof. Asko Ristolainen for integrating me into this incredible team for three months, and to Cecilia, Elizaveta, Jaan, Roza, Simon, and Walid for their wise counsel and assistance throughout my stay. I am also grateful to my students, Maurizio, Oscar, Daniel, and Álvaro, for their significant contributions to this work. I wish them all the best in their future careers and endeavors.

To all of my CAR colleagues, I am extremely grateful for your friendship and encouragement over the years. A special thanks goes to my main lab peers, Andres, Esther, Khalil, and William—your talent and kindness have inspired me to improve each day. I also extend my gratitude to Juan, Christyan, David, and Carlos for their invaluable help and friendship. Furthermore, I am thankful to the administrative staff, Esther, Rosa, and Carlos, for their assistance with travel arrangements, documents, forms, and countless other matters. A huge thank you to the technicians Pablo and Angel for their willingness to help me and countless other students. You truly are the heroes of the labs.

To all of my friends, thank you for the good times and your support throughout this journey. To the members of Wirillo—Claudio, Dupuy, Bonny, Francis, and Rafa—I am grateful for your friendship, continuous support, and the memories we have shared since we first met at USB almost 11 years ago. To my Aerodesign colleagues, thank you for the wonderful moments and our shared successes. To all my friends around the world, I appreciate the great times we have had together. Special thanks to Andrea, Augusto, Eric, Elizabeth, Verónica, Fernando, Louise, Ramón, Samuel, Oswaldo, Piercarlo, Carlos, and Reinaldo for your friendship.

I would especially like to thank my family for their constant support and for being a constant source of inspiration, encouraging me to strive for excellence in everything I do. Thank you, Mom and Dad, for exemplifying professionalism, honesty, and hard work, and for always caring for me and pushing me to be the best version of myself. To my brothers, thank you for being role models whom I admire and who motivate me to follow this path. I hold all the moments we have shared close to my heart.

Lastly, but certainly not least, I want to thank Cristina for being my light, my happiness, my motivation, and my strength over the past two years. Your unconditional support, even in the most challenging times, has helped me reach this moment in my life. You are my greatest source of inspiration and I will forever be grateful for all you have done and continue to do for me. I will always love you and I look forward to sharing the rest of my days with you.

Abstract

The extraction of raw materials through mining is essential to meet the growing global demand. Traditional mining methods face challenges in worker safety, operational efficiency, and environmental impact. Consequently, the mining sector is adopting advanced technologies, particularly robotics and automation, to improve processes. This shift is exemplified by initiatives like the ROBOMINERS project, funded under the EU's Horizon 2020 Research and Innovation Program. ROBOMINERS aims to create a lower TRL technology base for radical innovations in mining, unlocking substantial reserves of new or unexploited resources within the EU. It focuses on introducing disruptive robotic concepts to facilitate mineral access in Europe, shaping a new mining ecosystem. Central to this vision is developing a modular robotic mining system. This approach involves drilling a large-diameter borehole into the mine and deploying separate modules through it. These modules autonomously self-assemble into a fully functional mining robot capable of complex tasks like selective mining and mine mapping. The site may be flooded or dry, requiring versatile robotic solutions.

Modular robotic systems offer a promising approach to overcome the limitations of traditional mining robots, providing versatility and scalability. These systems consist of interchangeable modules that can be rearranged, detached, and recombined for various tasks, offering greater flexibility than conventional monolithic designs. However, developing modular robotic systems for underground mining poses unique challenges, including robust inter-module coupling and communication, adaptable locomotion for irregular terrain, efficient power distribution, and maintaining functionality in harsh conditions. Despite these challenges, their adaptability makes them compelling for dynamic mining operations.

This dissertation introduces a novel modular robotic system designed to study modularity, self-assembly, and reconfiguration capabilities in mining environments. The thesis presents the design, development, and testing of various technologies within this system, including modular mobile platforms with manually configurable locomotion submodules and self-assembly capabilities using an adaptable coupling mechanism, as well as additional robotic modules for sensing and mining tasks. The prototypes serve as a test platform to investigate how modularity can enhance the development of future mine-ready platforms, capable of on-site reconfiguration to perform various mining tasks efficiently and safely.

This doctoral thesis addresses key technical challenges, including inter-module self-assembly and communication, terrain-adaptable locomotion, alternative mapping techniques, and reconfiguration in underground mining conditions. Through analysis and experimentation, the thesis demonstrates the potential of applying a modular approach to enhance the versatility and robustness of mining operations. The findings contribute to the broader field of mining robotics and offer valuable insights into developing adaptable robotic systems for complex industrial environments.

This Compendium thesis consists of three peer-reviewed articles published in scientific journals, collectively fulfilling the goals of the doctoral thesis and maintaining thematic alignment. These articles have advanced the state of the art in modular robotic systems, the application of soft robotic arms as coupling mechanisms, and the use of whisker sensors for 3D mapping tasks.

Resumen

La extracción de materias primas mediante la minería es esencial para satisfacer la creciente demanda mundial. Los métodos mineros tradicionales se enfrentan a retos en materia de seguridad, eficiencia operativa e impacto medioambiental. Como consecuencia, el sector minero está adoptando tecnologías avanzadas, en particular la robótica y la automatización, para mejorar los procesos. Un ejemplo de este cambio son iniciativas como el proyecto ROBOMINERS, financiado por el Programa de Investigación e Innovación Horizonte 2020 de la UE. ROBOMINERS pretende crear una base tecnológica de TRL bajo para innovaciones disruptivas en minería, desbloqueando importantes reservas de recursos sin explotar en la UE. El proyecto se centra en la introducción de conceptos robóticos disruptivos para reactivar la minería en Europa, dando forma a un nuevo ecosistema minero. Un elemento central de esta visión es el desarrollo de un sistema modular de minería robotizada. Este planteamiento consiste en perforar un pozo de gran diámetro en la mina y desplegar módulos independientes a través de él. Una vez en la mina, estos módulos se autoensamblan de forma autónoma en un robot minero funcional capaz de realizar tareas complejas como la minería selectiva y la cartografía minera. El yacimiento puede estar inundado o seco, lo que exige soluciones robóticas versátiles.

Los sistemas robóticos modulares ofrecen una alternativa prometedora para superar las limitaciones de los robots mineros tradicionales, ya que proporcionan versatilidad y escalabilidad. Estos sistemas constan de módulos intercambiables que pueden reorganizarse, separarse y recombinarse para diversas tareas, lo que ofrece mayor flexibilidad que los diseños monolíticos convencionales. Sin embargo, el desarrollo de sistemas robóticos modulares para minería subterránea plantea retos únicos, como la robustez del acoplamiento y la comunicación entre módulos, la locomoción adaptable a terrenos irregulares, la distribución eficiente de energía y el mantenimiento de las funcionalidades en condiciones adversas. A pesar de estos retos, su adaptabilidad los hace atractivos para las operaciones mineras.

Esta tesis doctoral introduce un novedoso sistema robótico modular diseñado para estudiar las capacidades de modularidad, autoensamblaje y reconfiguración en entornos mineros. La tesis presenta el diseño, desarrollo y prueba de diversas tecnologías, incluyendo plataformas móviles modulares con submódulos de locomoción configurables manualmente y capacidades de autoensamblaje mediante un mecanismo de acoplamiento adaptable, así como módulos robóticos adicionales para tareas de mapeado y minería. Los prototipos sirven como un banco de prueba para investigar cómo la modularidad puede mejorar el desarrollo de futuras plataformas listas para la minería, capaces de reconfigurarse in situ para realizar diversas tareas mineras de manera eficiente y segura.

La tesis doctoral aborda desafíos técnicos clave, incluyendo el autoensamblaje y la comunicación entre módulos, la locomoción adaptable al terreno, técnicas alternativas de mapeado y la reconfiguración en condiciones de minería subterránea. A través del análisis y la experimentación, se demuestra el potencial de aplicar un enfoque modular para mejorar la versatilidad y robustez de las operaciones mineras. Los resultados contribuyen al campo de la robótica minera y ofrecen valiosas perspectivas para el desarrollo de sistemas robóticos adaptables para entornos industriales complejos.

Esta tesis doctoral está compuesta por un compendio de tres artículos revisados por pares y publica-

dos en revistas científicas, que cumplen colectivamente los objetivos de la tesis doctoral y mantienen la alineación temática. Estos artículos han avanzado el estado del arte en sistemas robóticos modulares, la aplicación de brazos robóticos blandos como mecanismos de acoplamiento, y el uso de sensores de contacto tipo *whisker* para tareas de mapeado 3D.

Table of Contents

Acknowledgement v
Abstract vi
Resumen vii
List of Figures x
List of Tables xv
Abbreviations and acronyms xviii
List of Publications xxi

1 Introduction **1**
1.1 Motivation and Framework of the Thesis 2
1.2 Objectives 5
1.3 Contributions 6
1.4 Outline 6

2 State of the art **9**
2.1 Underground Mining Robots 9
2.1.1 Function of robots in underground mining environments 13
2.1.2 Locomotion methods of subterranean robots 23
2.2 Mobile Modular Robotic Systems 37
2.2.1 Self-assembly mechanisms for modular reconfigurable robots 40
2.3 Alternative sensing technologies for unstructured underground environments 43

3 Research Methodology **45**
3.1 ROBOMINERS mining concept 45
3.2 Methodology Process 48
3.3 Technology Readiness Levels 50

4 Results and Discussion **53**
4.1 Modular Robotic System Description (Publication **P.I**) 54
4.1.1 Introduction 54
4.1.2 Hardware description 55
4.1.3 RM2 module leg mechanism 56
4.1.4 Robotic system configuration and locomotion experiments 59
4.2 Soft Robotic Coupling Mechanism for Modular Robots (Publication **P.II**) 61
4.2.1 Introduction 61

4.2.2 Hardware description . . . 62
4.2.3 Soft Continuum arm modeling . . . 64
4.2.4 RM2 coupling experiments . . . 67
4.3 Whisker-based sensing module for environment reconstruction (Publication **P.III**) . 68
4.3.1 Introduction . . . 68
4.3.2 Hardware description . . . 69
4.3.3 Sensor modeling . . . 70
4.3.4 3D-mapping experiments . . . 73

5 Conclusions **75**
5.1 Future Work . . . 76

Publications **79**
Publication I . . . 81
Publication II . . . 107
Publication III . . . 123

Appendices **139**

A Scientific Dissemination **141**
A.1 Journal Publications . . . 141
A.2 Conferences . . . 141
A.3 Patents . . . 142

B Unpublished results **143**
B.1 Vision system for self-assembly mechanism . . . 143
B.2 Active sensing mechanism . . . 145
B.2.1 Mechanism modeling . . . 145
B.2.2 3D Mapping experiments . . . 148

References **151**

List of Figures

2.1 Underground mining robots classified according to their principal mission/function. 13

2.2 Examples of underground mining exploration platforms. (**A**) Terregator autonomous exploration robot (Champeny-Bares et al., 1991). (**B**) CSIRO Numbat (Ralston and Hainsworth, 1998). (**C**) GroundHog (Baker et al., 2006).(**D**) Cave Crawler (Morris et al., 2006). (**E**) MPI mine inspection robot (Kasprzyczak et al., 2016). (**F**) Autonomous Driving Patrol Robot (Kim and Choi, 2023). 14

2.3 Underground mining robot systems for surveying tasks, specifically teams competing in DARPA SubT Challenge. (**A**) CERBERUS team (Tranzatto, Mascarich, et al., 2022). (**B**) CSIRO Data61 team (Hudson et al., 2022). (**C**) MARBLE team (Ohradzansky et al., 2022). (**D**) Explorer team (Cao et al., 2023). (**E**) CoSTAR team (Agha et al., 2021). (**F**) CTU-CRAS-Norlab team (Rouček et al., 2020a). 16

2.4 Mine rescue robot examples. (**A**) ANDROS Wolverine V2 (Reddy et al., 2015). (**B**) Gemini Scout (Dodge, 2020). (**C**) MSRBOTS multi-robot system (J. Zhao et al., 2017). (**D**) Telerescuer (Novák et al., 2018). (**E**) CUMT-I and CUMT-V mine rescue robots (Y. Li et al., 2020). 19

2.5 Underground excavation robot examples. (**A**) Molebot multitracked prototype (Lee et al., 2023). (**B**) Seabed excavation Robot SEAVO (Isaka et al., 2019). (**C**) Badger tunneling robot (Vartholomeos et al., 2021). 21

2.6 Underground mining robots classified according to the locomotion capabilities . . . 24

2.7 Examples of tracked underground mining robotic platforms. (**A**) CSIRO BIA5 All Terrain Robot (ATR) climbing a steeped slope (**right**) and serving as a marsupial platform to deploy UAVs (**left**) (Hudson et al., 2022). CSIRO Dynamic Tracked Robot (DTR) (Hudson et al., 2022). (**C**) CTU-CRAS-Norlab Absolem robot (Rouček et al., 2020a). (**D**) MINBOT-II mine rescue robot (W. Wang et al., 2017). 25

2.8 Examples of underground mining terrestrial platforms with Wheeled locomotion methods. (**A**) Rhino mine surveying platform (Tatsch et al., 2023). (**B**) Alexander autonomous mapping robot (Plotnikov et al., 2020). (**C**) Explorer SubT Challenge R1,R2,R3 mine robot explorers (Cao et al., 2023).(**D**) ARIDuA project Julius underground mining robot (Plotnikov et al., 2020). 26

2.9 Examples of underground mining terrestrial platforms with biomimetic locomotion methods. (**A**) CERBERUS Anymal SubT Challenge version (Tranzatto, Mascarich, et al., 2022). (**B**) Boston dynamic Spot equipped with sensory system for Marble (**left**) and CoSTAR (**right**) teams competing in DARPA SubT challenge (Agha et al., 2021; Ohradzansky et al., 2022). (**C**) Csiro Data61 Bruce Hexapod Steindl et al., 2020 (Hudson et al., 2022). (**D**) CTU-CRAS-Norlab Legged robots: HEBI robotics Lily (**left**) and Scarab II crawling Hexapods (**right**) (Forouhar et al., 2021; Rouček et al., 2020a). 28

2.10 Examples of underground mining terrestrial platforms with hybrid locomotion methods. (**A**) Different configurations of EspeleoRobô (Azpúrua et al., 2021). (**B**) Spoked-Wheel locomotion method of HADES underground mine disaster scouting robot (Molyneaux, 2016). (**C**) GMRI Mine inspection platform featuring Wheels and legs acting as movable supports(Kasprzyczak et al., 2012). CoSTAR Telemax robot adapted for DARPA SubT Challenge (**D**) (Agha et al., 2021) 30

2.11 Examples of aquatic type mine exploring robots. (**A**) RoboBoat Villarroel et al., 2024. (**B**) Sparus-II AUV (Carreras et al., 2018). (**C**) Evolution of UX AUV robots during UNEXIN and UNEXUP projects (Pinto et al., 2020). 32

2.12 Examples of aerial robots that operates in underground mining environments. (**A**) Carnegie Mellon Explorer SubT custom built quadcopter (Cao et al., 2023). (**B**) CTU-CRAS-Norlab SubT custom Quadrotor (Rouček et al., 2020a). (**C**) Emesent UAV adapted by CSIRO SubT team (Hudson et al., 2022). (**D**) Alpha (**left**) and Gagarin (**right**) UAV for CERBERUS SubT Challenge (Tranzatto, Mascarich, et al., 2022). (**E**) Oxpecker inspecting a stone mine wall (Martinez et al., 2023). 33

2.13 Examples of underground mining platforms with hybrid means of transportation. (**A**) Amphibian Sub-Terranean robot (Maity and Majumder, 2014). (**B**) Buoyant crawler (Martz et al., 2020). (**C**) Aerial/Terrestrial Rollocopter (Agha et al., 2021; Fan et al., 2019). (**D**) Aerial/Terrestrial Drivocopter (Agha et al., 2021; Kalantari et al., 2020). 35

2.14 Examples of modular, self-reconfigurable mobile robotic systems. (**A**) CEBOT robotic system (Fukuda and Nakagawa, 1988). (**B**) Milibot train (Brown et al., 2002).(**C**) S-BOT robotic system (Mondada et al., 2004). (**D**) JL-I train configuration for three robotic modules (**top**) and JL-2 module featuring coupling mechanism based on a manipulator (**bottom**) (Guanghua et al., 2006; W. Wang et al., 2010). (**E**) Reconfigurable tracked robot system SMMRob (H. Li et al., 2022) 38

2.15 Examples of manipulator-based coupling mechanism for modular self-reconfigurable robots. (**A**) S-Bot rigid gripper (**top**) and flexible gripper (**bottom**)(Mondada et al., 2004). (**B**) JL-2 manipulator with spherical joint mechanism (W. Wang et al., 2010).(**C**) SMMRob docking mechanism (**left**) and joint actuation mechanism (**right**) (H. Li et al., 2022). 41

2.16 Examples of whisker sensor implementations in robotics. Top row: Implementations in mobile robots. (**A**) Whiskerbot (Pearson et al., 2007). (**B**) Shrewbot (Pearson et al., 2013). (**C**) SCRATCHbot (Pearson et al., 2010). (**D**) Whisker-RatSLAM Applied to navigation (**left**) and 6D Object Identification (**right**) (Salman and Pearson, 2016a, 2018). (**E**) Contact Localization on UR robot manipulator (Lin et al., 2022) 44

3.1 ROBOMINERS concept. (**Left**) Deployment of modular prototypes through a borehole to later self-assemble and perform underground mining operations (Stein and Correia, 2023). (**Right**) Bioinspired mining layout using a part-face cutter head on a tethered robotic miner in a keyhole mining operation (Pinkse et al., 2022). . . 46
3.2 ROBOMINERS prototypes. (**Left**) RM1 full-scale robotic miner (Hakonen et al., 2023). (**Center**) RM2 scaled model. (**Right**) RM3 lab prototype (Piho et al., 2023). 47
3.3 Robotic modular system conceptual drawing specifying the main components of the system, including the active and passive ports, terrain-adaptable mechanism, modular design and compact design 49
3.4 General workflow in the development of mechatronic systems according to VDI 2206 guideline (Gausemeier and Moehringer, 2002). 50
3.5 Integration of subsystems over time to the modular robotic system RM2. 50
3.6 Technology Readiness Levels (TRL) diagram to represent the level of maturity of the solutions presented by this thesis. 52

4.1 Publications diagram used for this thesis by compendium, highlighting the interrelation and differences. 53
4.2 Modular robotic conceptual solution that allows collaboration between robotic modules to perform more complex tasks in mining environments. (**a**) Different robotic modules are deployed in a mine. (**b**) The robotic module that features the cutting head ask the other robotic module to assemble to perform a mining task and a coupling maneuver is performed to form a larger robotic structure. (**c**) The resulting structure, made up of two mobile platforms and a cutting module, is assembled to perform mining tasks. 55
4.3 Description of the RM2 Robotic System: Each individual robotic module is equipped with three compartments and three docking ports. These versatile docking ports are used to configure a range of locomotion submodules or integrate additional sensors. The compartments house various internal components, while the robot arm facilitates the coupling of different modules, enabling the formation of more intricate and complex robotic systems. 56
4.4 RM2 Leg mechanism mechanical model. The motor input angles q_1, q_2 and q_3 are presented in red, while the resulting position of point of interest $B = (B_x, B_y)$ and orientation ϕ is in green. The relative angles between links L_{1i} and L_{2i} are represented in blue. 57
4.5 RM2 Leg mechanism resulting workspace. 59
4.6 Reconfigurability tests for the RM2 robotic modules with different locomotion submodules 60
4.7 Slope climbing test for different locomotion submodules. On the left, the RM2 module features screws, while on the right uses track wheels. 60
4.8 Soft Continuum arm as coupling mechanism. (**A**) Car crane principle for docking robots or tool modules. (**B**) First, the soft continuum arm is guided to the module/tool docking port. (**C**) Then, the end effector docking mechanism secures the module/tool. (**D**) Finally, the arm is retracted back to the module securing and attaching the desired part. ©2023 Mary Ann Inc 61

4.9 Hardware Description of the Soft Robotic Arm in the Modular Robotic Prototype. The arm showcases a composition of flexible racks, rigid disks, and servomotors integrated into the robot's frame. 62
4.10 Coupling mechanism hardware description. ©2023 Mary Ann Inc 63
4.11 Forward kinematic model validation. The red triangles represent the analytical model calculated position, while the blue circles are the ground truth ©2023 Mary Ann Inc 65
4.12 Inverse kinematic model validation. The red line represents the prediction of the ELM network, while the blue one represent the rack extension in mm. ©2023 Mary Ann Inc 67
4.13 Module coupling maneuvers: (a) Following a curved trajectory. (b) Following a straight trajectory. ©2023 Mary Ann Inc 68
4.14 Conceptual implementation of the whisker disc for enhancing the RM2 module navigation and mapping capabilities in underground mining environments. 69
4.15 Whisker based sensing module description: (a) the sensing disk comprises a circular array of 32 whisker sensors. (b) Single Whisker sensor section view. 70
4.16 Whisker Rotational model: The whisker rotates in two different angles from the pivotal point O, generating a change in the position and orientation of magnet M that is captured by the 3D Hall Effect Sensor S 70
4.17 Mean average error and root mean square error heatmap comparison between the ELM and analytical models tuned for a single whisker. 71
4.18 Mean average error and root mean square error heatmap comparison between the ELM and analytical models tuned for the whiskers combined dataset. 72
4.19 Environment reconstruction from the 3D-mapping experiment. 74
4.20 Processed point cloud analysis 74

B.1 Vision sytem for self-assembly mechanism. The camera module is installed in the leg of a mobile module, while the passive interface integrates a set of three equally distant ArUco codes. 143
B.2 Graphical representation of the passive port frame calculation as a function of the ArUco codes detected. A single code is enough to determine the position of the passive port pose. 144
B.3 Self-assembly coupling maneuver between two mobile modules. 144
B.4 Active Sensing Mechanism description. (a) The active sensing mechanism can improve the navigation capabilities of the modular platforms in underground mine environments. (b) The mechanism comprises a soft robotic arm embedded into the structure of a robotic module with an integrated sensing disk as the end effector . . 145
B.5 (**Left**) Data collection testbed affixed to the robotic module to capture the position and orientation of the tip of the Active Sensing Mechanism. (**Right**) Active sensing mechanism workspace derived from the data capture procedure. The top view is the XY plane, while the bottom shows the XZ plane. Each point represents the midpoint of the whisker disk. 146
B.6 Validation test for the Forward Kinematics comparing the position of the center of the disk (green triangle) against the data predicted by the NN (red circles). 147

B.7 3D mapping testbed setup and mapping experiment. The active sensing mechanism is guided towards the lower right corner of the box to perform environment reconstruction tasks. 148
B.8 Resulting pointcloud from mapped corner. The left view present an ISO view of the pointcloud, while the right subfigure presents a frontal view of the resultint pointcloud. 149
B.9 Distance between bottom, inclined and horizontal planes and the clustered point located within this planes. The error metric is the projected distance from the point and the plane. 149

List of Tables

2.1 Summary of underground mining robot solutions found in the literature 10

3.1 ROBOMINER prototypes technical specs. 47
3.2 Technology Readiness Level definitions and descriptions. Source: Hirshorn and Jefferies, 2016 51

4.1 Arm tip position estimation error using the direct kinematics model. ©2023 Mary Ann Inc 66
4.2 Arm tip orientation error using the direct kinematics model. ©2023 Mary Ann Inc 66
4.3 Rack extension error using the inverse kinematic model. ©2023 Mary Ann Inc . . 66
4.4 Whisker rotation model comparison for general models for the combined whisker dataset. 72
4.5 Maximum and average errors derived from the post-processed point cloud and the projected points onto the adjacent box surface. 74

B.1 Comparison of machine learning algorithms. Each algorithm was evaluated using the same test set. 147
B.2 Results for the validation of the NN 147
B.3 Maximum and average errors derived from the post-processed point cloud of the active mechanism and the projected points onto the adjacent box surface. 148

Abbreviations and acronyms

ABS Acrylonitrile Butadiene Styrene

ASV Autonomous Surface Vehicle

AU Actuation Unit

AUV Autonomous Underwater Vehicle

ATR All Terrain Vehicle

CAN Controller Area Network

CC Constant Curvature

CMOS Complementary Metal-Oxide-Semiconductor

COTS Commercial Off-the-Shelf

CRM Critical Raw Materials

CSIRO Commonwealth Scientific and Industrial Research Organization

DARPA Defense Advanced Research Projects Agency

DoF Degree of Freedom

DTR Dynamic Tracked Robot

EIT European Institute of Innovation and Technology

ELM Extreme Learning Machine

EU European Union

GPS Global Positioning System

I2C Inter-Integrated Circuit

IMU Inertial Measurement Unit

IoT Internet of Things

ISO Internacional Organization for Standardization

MAE Mean Average Error

MSHA Mine Safety and Health Administration

NASA National Aeronautics and Space Administration

NIOSH National Institute of Occupational Safety and Health

NN Neural Network

LiDAR Light Detection and Ranging

PCB Printed Circuit Board

PCC Piecewise Constant Curvature

PSD Position Sensitive Detector

RM2CM RM2 Coupling Mechanism

RMSE Root Mean Square Error

ROS Robot Operating System

SDG Sustainable Development Goal

SLAM Simultaneous Localization and Mapping

SMA Shape Memory Alloy

SubT Subterranean

TPU Thermoplastic Polyurethane

TRL Technology Readiness Level

UAV Unmaned Aerical Vehicle

UGV Unmaned Ground Vehicle

UN United Nations

UPM Universidad Politécnica de Madrid

VDI Association of German Engineers (Verein Deutscher Ingenieure)

List of Publications

The following thesis by compendium is based on the work and results presented in the following three journal publications, chosen from the scientific dissemination shown in Appendix A, hereby referenced in the text as **P.I–P.III**:

P.I Gomez, V., Hernando, M., Aguado, E., Sanz, R., & Rossi, C. (2023). *ROBOMINER: Development of a Highly Configurable and Modular Scaled-Down Prototype of a Mining Robot.* Machines, 11(8), 809. doi.org/10.3390/machines11080809

P.II Gomez, V., Hernando, M., Aguado, E., Bajo, D., & Rossi, C. (2024). *Design and Kinematic Modeling of a Soft Continuum Telescopic Arm for the Self-Assembly Mechanism of a Modular Robot.* Soft Robotics, 11(2), 347–360. doi.org/10.1089/soro.2023.0020

P.III Gomez, V., Remmas, W., Hernando, M., Ristolainen, A., Rossi, C. (2024) *Bioinspired Whisker Sensor for 3D Mapping of Underground Mining Environments.* Biomimetics, 9(2):83. doi.org/10.3390/biomimetics9020083

Publication **P.I** introduces an innovative modular robotic system designed to explore concepts of modularity and self-assembly for potential mining applications. This scaled-down prototype consists of reconfigurable robotic modules that can be connected to form larger structures, along with attachable submodules for specific tasks such as mining or sensing. Key features include a soft robotic arm for coupling, interchangeable locomotion submodules, and specialized mining and sensing modules. This paper provides a detailed overview of the robotic system, along with the derivation of the kinematic models of the mobile platform. The experiments demonstrated successful coupling of the module, effective locomotion in various terrains, and operation of the mining module. Although using scaled-down prototypes, the concepts are intended to be able to be adapted to full-size mining robots in the future. The research aims to advance modular reconfigurable robotics for mining applications, with a focus on improving adaptability and versatility in challenging environments.

Publication **P.II** introduces a novel soft continuum arm that functions as a coupling mechanism for the mobile prototype presented in **P.I**. The arm consists of two extensible sections made of 3D-printed flexible racks and rigid disks, actuated by servomotors using a rack-and-pinion mechanism. It serves as a coupling mechanism to join robotic modules together, employing a car crane-inspired docking system. This paper details the mechanical design of the arm, the material selection process, and its kinematic modeling. The arm kinematics is addressed using both analytical and data-driven approaches. Forward kinematics are solved using a constant-curvature model and assuming independent bending across sections, while inverse kinematics utilize a machine learning algorithm based on an Extreme Learning Machine network. Experimental validation shows accurate results for both models, with maximum position errors below 4 mm for forward kinematics and a mean absolute error of less than 5 mm for inverse kinematics. The article demonstrates the arm's functionality through coupling maneuvers and discusses potential applications in mining robotics, including adaptable mapping strategies and module reconfiguration.

Publication **P.III** presents the development of a bioinspired whisker sensor disk for 3D mapping in underground mining environments. The paper offers a detailed description of the sensing head,

including its manufacturing process. The sensing head consists of a circular array of 32 whisker sensors, each comprising a flexible rod, magnet holder, and 3D Hall-effect sensor. Whisker deflections were modeled using both analytical and data-driven approaches, with the data-driven algorithm providing superior accuracy and efficiency. The models are validated by testing pairs of whisker rotation angles and sensor measurements. The most effective model is subsequently used for an environment reconstruction task in a simplified model of an underground mine to validate the sensing module. The sensor disk was initially tested on an industrial manipulator, successfully mapping a box-shaped environment with near-millimeter precision. The results demonstrate the potential of this touch-based sensing technology for navigating and mapping challenging underground environments where dust and darkness hinder traditional methods.

In all publications **P.I–P.III**, the author of this thesis was responsible for the design, implementation, testing, and validation of the solutions, as well as the manuscript writing process. In **P.II**, the co-author D. Bajo Collados contributed to the design and data collection process, whilst in **P.III**, the co-author W. Remmas contributed to the post-processing of the data in the execution of the mapping experiments. In general, the co-authors in every publication have contributed to the conceptual theoretical suggestions, as well as to the assistance in the manuscript editing and review process.

Chapter 1

Introduction

"The beginning is the most important part of the work."

– Plato

The demand for robotic solutions capable of operating in unpredictable and challenging environments, such as disaster areas, mining environments, space exploration, and industrial facilities with potential risks, has experienced accelerated growth due to major advances in the field. Today's field robots are adept at traversing dangerous terrains, executing repetitive tasks accurately, and reducing the hazards that the human presence brings into dangerous settings (Marshall et al., 2016).

In the mining industry, the search for efficiency, safety, and sustainability is currently driving the exploration of innovative technologies. The harsh and often hazardous environments of mining sites require the development of methods that not only improve productivity, but also prioritize worker well-being, while minimizing environmental impact in accordance with existing government emission standards. As a result, the integration of automation and robotic technologies has recently seen rapid expansion to address these issues, offering the possibility of radically changing age-old problems and possibly altering traditional mining operations into a new paradigm (Lopes et al., 2020).

According to Hartman and Mutmansky, 2002, the entire sequence of activities in contemporary mining can be divided into five phases of the mine life cycle: prospecting, exploration, development, exploitation, and reclamation. Robotic technologies have found widespread application in several of these phases, particularly in exploration, development, and exploitation (Marshall et al., 2016). During the exploration and development stages, robots play a crucial role in accurately identifying resources, including those in underwater and extraterrestrial environments, and in the efficient construction of mining infrastructure. In the exploitation stage, robotic automation facilitates the extraction, processing, and transportation of materials. The adoption of robotics has greatly improved these mining processes, enhancing safety and productivity while reducing human exposure to dangerous conditions.

In particular, search and rescue robots have played an essential role in the advancement of robotic capabilities for harsh mining conditions. These specialized robots are designed to navigate through dangerous and dynamic environments, such as collapsed mine shafts, areas with toxic gas leaks, or zones affected by underground fires or explosions. Their ability to operate in these high-risk situations

has been instrumental in saving lives and mitigating disasters, while also driving innovation in the development of robust, durable, and adaptable robotic platforms. Search and rescue applications in mining have highlighted the critical need for versatile robotic systems capable of adapting to unstructured, unpredictable environments, thereby paving the way for more resilient and flexible mining robots.

Despite substantial progress made in integrating robotics into mining operations, current systems often face limitations in terms of versatility and scalability. The harsh conditions found in mining environments, including lack of lighting, challenging communication infrastructures, inadequate localization techniques, uneven terrain, and dynamically changing surroundings, pose significant challenges for both human workers and robotic systems. These obstacles emphasize the need to develop more adaptable and flexible robotic solutions that can meet the evolving demands of modern mining operations while ensuring safety and operational efficiency.

Modular robotic systems offer a promising solution to overcome the limitations of conventional mining robots. Due to their inherent design, modular robots provide significant advantages in terms of versatility and scalability. These systems are composed of interchangeable modules that can be rearranged, detached, and recombined to suit various tasks and environments, offering more flexibility compared to traditional monolithic robotic designs (Dokuyucu and Özmen, 2023). In addition, modular robots often possess self-repair and self-replication abilities, which enhance their robustness and autonomy in challenging mining conditions. However, the development of modular robotic systems for underground mining poses unique challenges. These challenges include the need for reliable inter-module communication, adaptable coupling interfaces to navigate irregular terrain, efficient power distribution among modules, and the capability to maintain structural integrity and functionality in harsh, dusty, and potentially flooded conditions. Despite these challenges, the adaptability of modular robots makes them a compelling solution for the dynamic and unpredictable nature of mining operations.

This thesis by compendium aims to present a novel modular robotic system to study modularity, self-assembly and reconfiguration during operation concepts to perform different mining tasks. This system serves as a proof-of-concept version of a real mining robot that can be later transferred to future mine-ready platforms. By leveraging the inherent advantages of modularity, the proposed system aims to enhance versatility, scalability, and robustness, enabling more efficient and safer mining operations.

1.1 Motivation and Framework of the Thesis

As noted by Grohol and Veeh, 2023, the European Union is heavily relying on the importation of raw materials, especially minerals and metals, which account for more than 50% of total dependence on importation and up to 100% for essential commodities. Although Europe has significant potential to source these materials domestically, it has not fully exploited its deposits or optimized the processing of these materials into products and machinery. Lopes et al., 2020 points out that many European deposits still contain valuable mineral raw materials, including minerals that were overlooked during the operational period of closed mines (such as germanium in certain lead and zinc mines) and are now considered critical resources. The closure or disinterest in these mines is often attributed to economic factors (low financial returns, costs of mine dewatering), environmental

concerns (pollution of nearby water sources, ecosystem destruction) and technological hurdles (communication systems, ultra-deep mining), rather than the exhaustion of mineral resources.

To address the challenges posed by the mining environment, there is growing emphasis on the development of mining robots as a promising solution. These types of robots equipped with specialized mineral sensors, advanced and optimized drilling techniques, multi-terrain mobility systems, and modular architectures can offer improved endurance, precision, and risk management capabilities. By reducing human exposure to hazardous conditions, optimizing the mining process, and mitigating the environmental impacts associated with mining activities, mining robots offer a promising alternative to traditional methods. However, it is crucial to acnkowledge that developing and deploying mine-ready solutions requires extensive research and platform testing, leading to high implementation expenses. Consequently, developing technology demonstrators that address specific requirements and subsequently maturing and integrating the resulting technologies into a fully operational platform is often a more cost-effective approach.

Recognizing the essential need for a steady and cost-effective supply of raw materials, the European Union has tackled this challenge through innovative policies, strategic tools, and research and development funding. Programs like the Raw Materials Initiative[1], the European Innovation Partnership, and funding schemes such as Horizon 2020 and EIT KIC[2] are driving the EU to the cutting edge of technological advancement. The objective is to motivate European companies to implement innovative outcomes that result in enhanced security in the supply of raw materials from domestic sources within the EU.

Concretely, the societal challenge 5 of the Horizon 2020 programme[3], aims at transitioning to a greener, more resource efficient, and climate-resilient economy that harmonizes with the natural environment. This demonstrates a strong dedication to supporting UN's Sustainable Development Goals (SDGs) and the objectives of the COP21 Paris Agreement. Within this work programme, the topic call *SC5-09-2018-2019: New solutions for the sustainable production of raw materials* specifically address the issue of *"Securing sustainable access to raw materials, including metals, industrial minerals and construction raw materials, and particularly Critical Raw Materials (CRM)..."*. In this context, *"...There is also a need for very innovative and sustainable raw materials production solutions at lower TRLs to bring the next 'digital generation' to the raw materials field"*.

The ROBOMINERS[4] project, funded under the European Union's Horizon 2020, Research and Innovation Program, Societal Challenge 5, aims at *creating a lower Technology Readiness Level (TRL) technology base for radical innovations within the next decades in the sectors concerned that would help unlock substantial reserves of new or currently unexploited resources within the EU*. The project focuses strategically on the introduction of disruptive robotic concepts that facilitate access to minerals in Europe, thereby shaping a new mining ecosystem. ROBOMINERS presents a solution for developing Europe's small but high-grade mineral deposits such as vein-type mineralisations. In this application scenario, a large diameter borehole is drilled to the mineral deposit and the modular miner is deployed. The site may or may not be flooded depending on the local hydrogeological conditions.

[1] https://ima-europe.eu/eu-policy/industrial-policy-and-circular-economy/raw-material-initiative/
[2] https://eitrawmaterials.eu/
[3] https://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-climate_en.pdf
[4] https://robominers.eu/

An essential aspect of the ROBOMINERS project is modularity, ensuring that mining robots possess the ability to adapt and complete tasks in the face of new situations or disturbances, further improving the sustainability and efficiency of mining operations (Lopes et al., 2020). Therefore, central to the vision of the ROBOMINERS project is the development of a modular robotic mining system. This innovative approach involves sending separate modules to the mine through a large-diameter borehole. Once in the mine, these modules will autonomously self-assemble, forming a fully functional mining robot to perform complex tasks, such as selective mining and mine mapping. What distinguishes this system is its ability to reconfigure during operation, allowing it to cope with failures or adapt to various scenarios. This modular robotic system represents a groundbreaking advancement that promises greater flexibility and problem solving capabilities in mining operations, ultimately contributing to the broader goal of a more sustainable and efficient mining industry.

Developing and deploying modular robots involves numerous challenges and drawbacks. The architecture of a modular system is generally more complex than that of a fixed system, requiring careful planning for module interfaces, compatibility, interaction, and scalability. Each module must operate independently, while also being able to connect, share power, and communicate with other modules to form a larger, more complex system. This requires a well-designed module structure with robust terrain adaptation mechanisms and flexible coupling mechanisms for unstructured environments. Additionally, the system must include reconfiguring during operation abilities, adding another layer of complexity. Modules need to evaluate the current task, determine the best configuration, and execute the reconfiguration without disrupting ongoing operations. Despite these challenges, the advantages of a modular design are significant:

- **Versatility:** A modular robotic system can adapt to a wide range of tasks by reconfiguring into different structures. This is particularly beneficial in a mining context, where tasks can vary widely, from drilling and excavation to material transport and site inspection.
- **Scalability:** The system can be scaled up or down simply by adding or removing modules. This allows for a high degree of flexibility in terms of system size and capabilities.
- **Fault Tolerance:** If one module fails, it can be replaced without disrupting the entire system. This improves the reliability and longevity of the system, which are critical in a mining environment.
- **Cost Efficiency:** Instead of designing and building a separate robot for each task, a single modular system can be used for multiple tasks, leading to significant cost savings.

Therefore, the main motivation of this dissertation lies in the challenge to **address the existing limitations in mining robotics in terms of flexibility and adaptability by designing and developing a highly configurable modular robotic system capable of reconfiguring during operation to perform different tasks. By leveraging the principles of modularity and self-assembly**, this research explores **innovative solutions that can be scaled up for future robotic miners**, in line with the long-term vision of the ROBOMINERS project. Through an **in-depth investigation of mining robots and modular robotic design, autonomy, adaptability, and scalability**, this thesis by compendium contributes to the realization of **more efficient, versatile, and sustainable mining operations**.

1.2 Objectives

The main objectives of this thesis by compendium, addressed in included publications (**P.I–P.III**) can be summarized in a single sentence: *to conceptualize and prototype a suite of innovative technologies that explore modularity, resilience, and reconfigurability in platforms designed for underground mining environments, advancing them to a Technology Readiness Level 4 (TRL-4) to lay the groundwork for future mine-ready systems.* To achieve such a large scope objective, this dissertation seeks to attain the following subobjectives:

O.1 Modular prototype development for studying modularity and self-assembly capabilities in mining environments. Designing and developing functional prototypes that act as technology demonstrators for laboratory evaluation and testing of proposed technologies, components, scientific theories, and general robotics concepts is crucial for a swift, economical, and thorough assessment of new technologies before they are implemented in a mine-ready prototype. Although they are constructed with different techniques and materials and have limited capabilities, scaled prototypes should include both the functionality and the appearance of the final intended design.

- **O.1.1** *Modular robotic system conceptualization*: The development of a modular robotic system for mining must accomplish a previously set of requirements specified for the intended application.
- **O.1.2** *Terrain-adaptable locomotion mechanism*: Mobile modules must feature mechanisms to adapt to irregular terrains similar to those of underground mining environments (muddy, partially flooded). Additionally, the mechanism should allow for the easy installation of different locomotion methods in the robotic module.

O.2 Novel adaptable self-assembly mechanism for modular mining robots. The development of a robust and highly adaptable solution is crucial to give the modular robotic system the ability to reconfigure during operation, to expand the configurations achievable by the system to carry out different functions within the mining environment.

- **O.2.1** *Coupling mechanism working principle*: By addressing specific requirements derived from application scenarios, the goal is to create a solution capable of adapting to unstructured environments while ensuring a straightforward design for seamless integration into robotic modules.
- **O.2.2** *Arm modeling*: The formulation of a precise mathematical model will illustrate the mapping of kinematic variables. Essentially, the model must identify the relationship between motor input and the end-effector's spatial position and orientation. Consequently, a detailed non-linear mathematical model of the coupling arm is necessary to conduct coupling experiments between robotic modules.

O.3 Contact-based, 3D-mapping sensor for unstructured environments. The primary focus is to develop a compact and adaptable solution that allows the system to perform environment reconstruction tasks in complex and dynamic environments, using contact-based sensors.

- **O.3.1** *Modular design*: The prototype must consist of a robotic module that can be seamlessly coupled to the robotic system, enabling the system to perform mapping tasks during

operation.

O.3.2 *Sensor modeling*: The formulation of an accurate sensor model will describe the behavior of physical variables, such as magnetic field intensity vectors, in terms of kinematic variables. In other words, the model must derive the relationship between sensor output and the whisker sensor rotational angles. Consequently, a detailed non-linear sensor model of the 3D-mapping sensor is essential.

O.4 System validation. Experimental evaluation of the prototype functionality must be carried out to verify and validate the proposed solutions. The experimental tests to be performed include validation of the locomotion methods and capabilities of the robotic system, such as self-assembly and the ability to collaborate with other robotic modules to perform complex tasks, such as mining or sensing unstructured environments.

1.3 Contributions

The main contributions of this thesis by compendium focuses on the design and development of the different modules and submodules of the modular mining robotic system. These are as follows:

C.1 A set of scaled, functional **robotic mobile modules**, hereby named RM2, is designed, manufactured and tested to be used as a proof-of-concept test bench platform to study and implement modularity and submodularity, manual and self-configuration, energy-sharing and self-assembly capabilities. This allows testing algorithms over physical platforms.

C.2 A **mathematical model** of the compact, parallel planar mechanism of the RM2 module leg that is capable of controlling position in a plane, as well as pitch and yaw rotational angles to adapt to irregular terrains.

C.3 A novel six DoF **adaptable, continuum coupling mechanism** that exploits the working principle of a car crane by enabling an assembly between different robotic modules in unstructured environments.

C.4 A **mathematical model** of the soft continuum arm derived from both analytical and data-driven approaches, by using the constant curvature model (CC) and an Extreme Learning Machine (ELM), respectively.

C.5 A whisker-based, **conceptual sensing head** designed to be used as an end-effector in different robotic arms or embedded into the robot's structure to perform 3D-mapping tasks in unstructured environments.

C.6 An experimentally validated, **data-driven** sensor model that predicts the location of the whisker tip, given the magnetic field intensity vector of a magnet comprising the sensing head robotic module.

1.4 Outline

The following thesis by compendium is composed of three publications **(P.I–P.III)**, which are presented in the Appendix A. The thesis is structured into **five** chapters, each serving a distinct

purpose:

Chapter 1 presents the motivation and framework of the thesis, as well as the main objectives and main contributions.

Chapter 2 provides an extensive review of literature on mining robots, emphasizing platforms that function in subterranean, unstructured settings. It also covers various modular mobile robot solutions, the deployment of diverse self-assembly mechanisms for these robots, and alternative sensing technologies applicable to mining environments.

Chapter 3 outlines the research context, details the methodology used for the thesis development, and assesses the results based on technology readiness levels.

Next, **Chapter 4** presents the experimental results and discussion, where the main results encompassed in publications (**P.I–P.III**) are presented. The results include the development and testing of the different robotic modules.

Lastly, **Chapter 5** presents the general conclusions of the doctoral thesis and an overview of future developments.

Chapter 2

State of the art

"If we knew what it was we were doing, it would not be called research, would it?"

– Albert Einstein

In recent years, significant advances in robotics, automation, and artificial intelligence have provided opportunities to address challenges in extreme environments, where the exploration of robotic concepts such as modularity, reconfiguration, self-assembly, and self-repair in unstructured environments has received considerable attention. This chapter conducts a literature review, specifically focusing on previous advances in mining robots, modular reconfigurable robots, self-assembly mechanisms, and alternative sensing technologies suitable for unstructured environments. The goal is to explore solutions that could prove beneficial for navigation and operations in complex and challenging environments, with a focus on underground mining operations.

2.1 Underground Mining Robots

The mining sector plays a vital role in advancing industrial capabilities by providing critical raw materials for various industries. In response to the evolving landscape, the mining industry is embracing change by adopting cutting-edge technologies such as automation, artificial intelligence, and robotics (Rogers et al., 2019). This strategic shift reinforces the industry's commitment to improving efficiency and staying at the forefront of technological advancement. Today, mining operations prioritize productivity, safety, and the pursuit of a technologically advanced and sustainable future (Lopes et al., 2020). Robotics is emerging as a key tool that can significantly address the various challenges of traditional mining methods, offering innovative solutions to promote cost-effective, sustainable, and responsible mining practices.

Although significant advances in automation and robotics are permeating the mining industry, the primary focus is on the efforts of mining companies to develop proprietary automated systems by integrating various sensors and control mechanisms into conventional mining machinery (Bołoz and Biały, 2020; Cucuzza, 2021; Darling et al., 2011). These developments, although classified as robotic advances in mining environments (Marshall et al., 2016), are not the subject of examination in this dissertation. In contrast, the objective of this section is to present the different developments that have been carried out in the scientific community to address the challenges that robots face

while operating in mining scenarios, specifically in underground mining environments. Therefore, this doctoral thesis explicitly excludes industrial applications of mining platforms adapted with sensors and control systems. Moreover, surface operations are excluded, thereby concentrating on solutions tailored specifically for subterranean environments. The solutions presented include robotic platforms designed to operate in unstructured environments that were adapted to underground environments with minor modifications, and platforms that are specifically designed to study different aspects of robotics in underground mining environments.

In this section, advancements are classified based on their primary role within the mine, with exploration, excavation, and search and rescue operations being the main activities; and their locomotion methods (terrestrial, aquatic, aerial, hybrid). Previous studies, such as Martz et al., 2020 and Plotnikov et al., 2020, have presented reviews focused on these categories. Nevertheless, these studies did not provide a comprehensive and detailed review of all historical and current records. Therefore, the subsequent sections present a more thorough examination of past significant advancements and future directions in the field of underground mining robots.

Table 2.1 shows the list of underground mining platforms introduced in the literature highlighting the robot name, the base platform, the mean of transport and locomotion method, and the type of solution and main function.

Table 2.1: Summary of underground mining robot solutions found in the literature

Source	Robot	Base Platform	Year	MoT	LM	ST	MF
Champeny-Bares et al., 1991	Terregator	Custom	1984	T	Wh	SR	Exp
Ralston and Hainsworth, 1998	Numbat	Custom	1986	T	Wh	SR	Exp
Reddy et al., 2015	Ratler	Custom	1998	T	Tr	SR	Exp
Reddy et al., 2015	Wolverine V-2	Wolverine	2001	T	Wh	SR	SaR
Baker et al., 2006	GroundHog	Custom	2002	T	Wh	SR	Exp
Morris et al., 2006	Cave Crawler	Custom	2006	T	Wh	SR	Exp
Dodge, 2020	Gemini-Scout	Custom	2008	T	Tr	SR	SaR
Maity and Majumder, 2014	Sub-Terranean robot	Custom	2013	Aq/T	H	SR	Exp
Carreras et al., 2013	SparusAUV	Custom	2010-2013	Aq	Th	SR	Exp
Y. Li et al., 2020	CUMT-I,II,III,IV,V	Custom	2006-2016	T	Tr	MR	SaR
Molyneaux et al., 2015	HADES	Custom	2016	T	H	SR	SaR
W. Wang et al., 2017	MINBOT-I,II	Custom	2016	T	Tr	SR	SaR
Kasprzyczak et al., 2016	MPI robot	Custom	2016	T	Wh	SR	Exp

MoT, Mean of Transportation; LM, Locomotion Method; ST, Solution Type; MF, Main Function; T, Terrestrial; Ae, Aerial; Aq, Aquatic; SR, Single Robot; MR, Multi Robot; Exp, Exploration; Exc, Excavation; SaR, Search and Rescue; Wh, Wheeled; Tr, Tracked; L, Legged; EW, Earthworm; H, Hybrid; Quad, Quadcopter; Th, Thrusters

Table 2.1: Summary of underground mining robot solutions found in the literature (Continued)

Source	Robot	Base Platform	Year	MoT	LM	ST	MF
Novák et al., 2018	TeleRescuer	Custom	2015-2017	T	Tr	SR	SaR
J. Zhao et al., 2017	MSRBOTS	Custom	2017	T	Tr	MR	SaR
D. Li et al., 2019	Mobile drilling robot	Custom	2018	T	Tr	SR	Exc
Isaka et al., 2019	SEAVO I,II	Custom	2019	T	EW	SR	Exc
Fujiwara et al., 2018	LEAVO	Custom	2019	T	EW	SR	Exc
Martz et al., 2020	Buoyant crawler	Custom	2020	Aq/T	H	SR	Exp
Lee et al., 2020	Mole-Bot	Custom	2020	T	Tr	SR	Exc
Grehl et al., 2015	Alexander	Husky A200	2017-2020	T	Wh	SR	Exp
Plotnikov et al., 2020	Julius	Innok Heros 444, UR5	2017-2020	T	Wh	SR	Exp
Vartholomeos et al., 2021	BADGER	Custom	2017-2020	T	EW	SR	Exc
Agha et al., 2021	Spot Husky Rollercopter Drivocopter Balto Telemax Quadrotor	Spot Husky A200 Custom Custom X-Maxx Telemax Pro Custom	2021	T T Ae/T Ae/T T T Ae	L Wh H H Wh H Quad	MR	Exp
Hudson et al., 2022	Spot Bruce Vision60 quadruped CSIRO DTR BIA5 ATR SuperDroid LT2-F Emesent UAV	Spot Custom Vision60 quadruped SuperDroid LT2-F BIA5 ATR SuperDroid LT2-F DJI M210	2021	T T T T T T Ae	L L L Tr Tr Tr Quad	MR	Exp
Tranzatto, Mascarich, et al., 2022	ANYmal B SubT Alpha Gagarin Armadillo Bravo Charlie	Anymal DJI M100 Custom Super Mega Bot DJI M100 DJI M100	2021	T T T T Ae Ae	L Quad Quad Wh Quad Quad	MR	Exp

MoT, Mean of Transportation; LM, Locomotion Method; ST, Solution Type; MF, Main Function; T, Terrestrial; Ae, Aerial; Aq, Aquatic; SR, Single Robot; MR, Multi Robot; Exp, Exploration; Exc, Excavation; SaR, Search and Rescue; Wh, Wheeled; Tr, Tracked; L, Legged; EW, Earthworm; H, Hybrid; Quad, Quadcopter; Th, Thrusters

Table 2.1: Summary of underground mining robot solutions found in the literature (Continued)

Source	Robot	Base Platform	Year	MoT	LM	ST	MF
Rouček et al., 2020a	Husky Absolem Hexapods Quadrotors	Husky A200 BlueBotics Absolem PhantomX Mark II DJI F450 kit	2021	T T T Ae	Wh Tr L Quad	MR	Exp
Cao et al., 2023	Spot R1,R2,R3 DS1, DS3, DS4 Canary	Spot Custom Custom Canary 15	2021	T T Ae Ae	L Wh Quad Quad	MR	Exp
Ohradzansky et al., 2022	Lumenier QAV500 SuperDroid HD2 Spot Husky	Lumenier QAV500 SuperDroid HD2 Spot Husky	2021	Ae T T T	Quad Tr L Wh	MR	Exp
Azpúrua et al., 2021	EspeleoRobo	Custom	2015-2021	T	H	SR	Exp
Martinez et al., 2023; Tatsch	Oxpecker Rhino	Custom Custom	2022	Ae T	Quad Wh	MR	Exp
Martins et al., 2018, 2020; Pinto et al., 2020	UX-1,2,MARA	Custom	2016-2022	Aq	Th	SR	Exp
Kim and Choi, 2023	Mine Scout	Agilex scout mini	2023	T	Wh	SR	Exp
Villarroel et al., 2024	RoboBoat	Carp Madness XXL	2024	Aq	Th	SR	Exp

MoT, Mean of Transportation; LM, Locomotion Method; ST, Solution Type; MF, Main Function; T, Terrestrial; Ae, Aerial; Aq, Aquatic; SR, Single Robot; MR, Multi Robot; Exp, Exploration; Exc, Excavation; SaR, Search and Rescue; Wh, Wheeled; Tr, Tracked; L, Legged; EW, Earthworm; H, Hybrid; Quad, Quadcopter; Th, Thrusters

2.1.1 Function of robots in underground mining environments

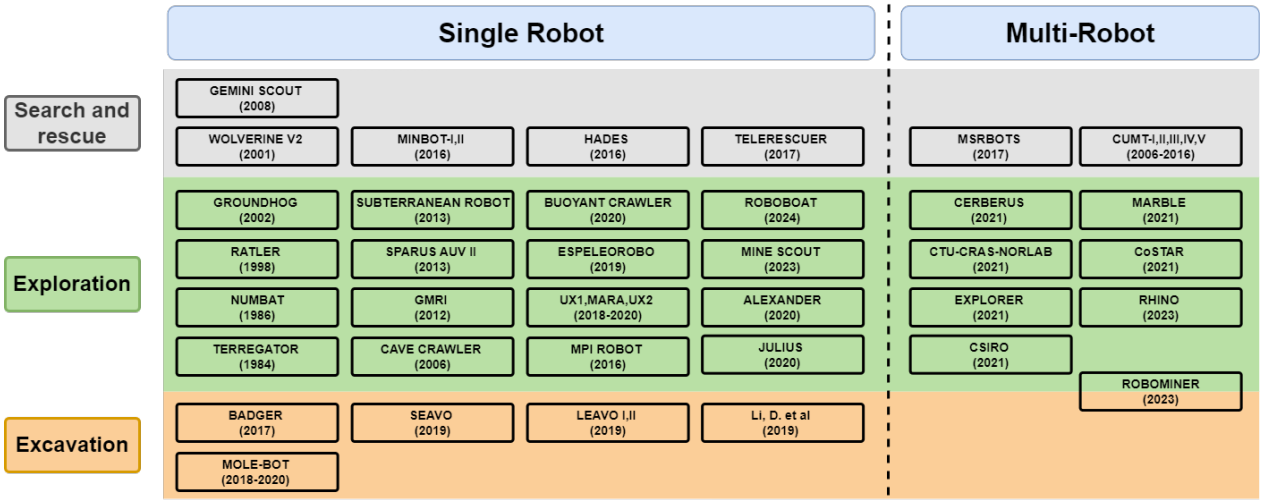


Figure 2.1: Underground mining robots classified according to their principal mission/function.

Operating in the depths of the Earth's subsurface presents a myriad of challenges, such as poor or no lighting, unpredictable terrain, flooding, GPS-denied environments, difficult-to-implement communications, deteriorating conditions over time, and even gas and dust explosions in coal mines. Robotics is proving to be an indispensable tool in this challenge, enabling engineers and researchers to navigate and exploit these harsh environments safely and effectively. From mapping natural caves and abandoned mine sites under a variety of conditions, testing different drilling strategies to later deploy them in the field or in outer space, to assisting rescue teams in past mine disasters, underground mining robots play an important role in enabling humans to navigate and exploit these extreme environments. Equipped with advanced sensory systems, innovative communication mechanisms, and robust locomotion systems, underground robotic systems can navigate narrow passages and uneven terrain to collect valuable data on geological formations and underground ecosystems.

Currently, underground robots used in mining settings can be divided into three primary categories based on their main role in the mine: search and rescue, exploration, and excavation. As shown in Figure 2.1, solutions are further divided into single-robot and multi-robot systems. This section outlines and examines the key advancements along with their main features and trends.

2.1.1.1 Exploration robots

Robots employed in underground mine exploration typically handle tasks such as navigation, mapping, and inspection of the mine's infrastructure, along with assessing safety conditions for human workers. The main differences between these methods usually refer to their complexity, flexibility, autonomy, robustness, and communication capabilities in unstructured environments.

Single-Robot Solutions

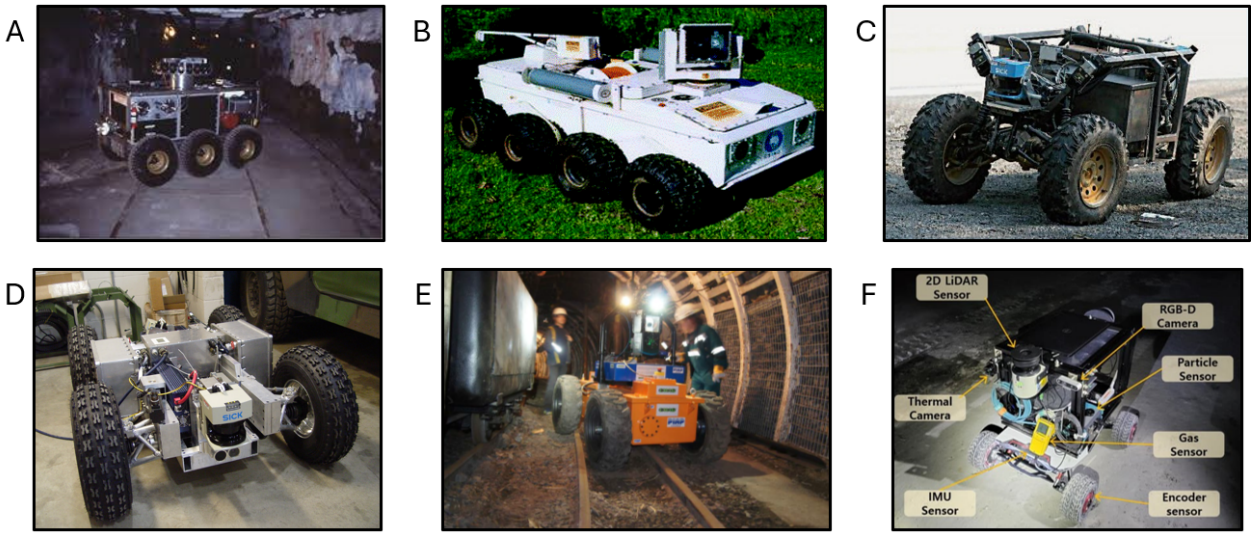


Figure 2.2: Examples of underground mining exploration platforms. (**A**) Terregator autonomous exploration robot (Champeny-Bares et al., 1991). (**B**) CSIRO Numbat (Ralston and Hainsworth, 1998). (**C**) GroundHog (Baker et al., 2006).(**D**) Cave Crawler (Morris et al., 2006). (**E**) MPI mine inspection robot (Kasprzyczak et al., 2016). (**F**) Autonomous Driving Patrol Robot (Kim and Choi, 2023).

The development of underground exploration robots in mining environments began in the early 1980s, when the Carnegie-Mellon Robotics Institute introduced the first autonomous robot to navigate an underground environment, Terregator (Figure 2.2A). Developed in 1984, Terregator (short for Terrain Navigator) is a remotely operable six-wheel, skid-steer vehicle that can autonomously navigate to a commanded position using its on-board computer and sensor system. The robot achieved semi-autonomous navigation using a combination of sonar and laser scanners for position estimation and obstacle avoidance (Champeny-Bares et al., 1991).

Shortly after, the Commonwealth Scientific and Industrial Research Organization (CSIRO) presented Numbat in 1986. This robot, intended as a search and rescue robot, has been used mainly to survey several underground mines at different sites in Australia. Numbat, depicted in Figure 2.2 B, consists of a 2.5 x 1.65 m teleoperated mobile platform with eight wheels. The robot incorporates a set of four cameras to guide the operator and a sonar sensor to navigate in poor light conditions. Different sensors were also present to analyze the concentration of gases, as well as airflow measurement. Numbat was constructed with a pressurized steel body to withstand possible explosions that could occur during navigation. Communication with the control station was carried out using an optical fiber cable (Ralston and Hainsworth, 1998).

In the early 2000s Carnegie's subterranean robotics team presented The Groundhog Robot for exploration and mapping tasks in deep underground mines. Developed in 2002, The Groundhog robot (Figure 2.2C) is a 700 kg four-wheel mobile mine mapping robot. The robot is less than 1 m tall and 1.2 m wide and is equipped with onboard computing, laser range sensing, gas and sinkage sensors, and video recording equipment, all protected in an explosion-proof steel enclosure (Baker et al., 2006). The Groundhog has been tested in several abandoned mines, where different

capabilities of the robot have been validated, including 3D mapping and autonomous navigation in some sections of the mines (Thrun et al., 2004). The next iteration of Groundhog, named Cave Crawler (Figure 2.2D), was presented in 2006. The robot has a modified chassis design that increases its agility and allows it to rotate in place, and it is equipped with a more sophisticated set of sensors. (Morris et al., 2006).

During the last 20 years, the sector has experienced rapid growth, fueled by several European initiatives, including the Mining-RoX and ARIDuA projects, which introduced Alexander (Grehl et al., 2015) and Julius (Plotnikov et al., 2020). The EMAG-PIAP consortium developed the MPI mine inspection platforms (Kasprzyczak et al., 2016), shown in Figure 2.2 D, and GMRI (Kasprzyczak et al., 2012). Furthermore, the UX series of underwater robots was developed through the UNEXMIN and UNEXAP projects (Pinto et al., 2020). In addition, the importance and contributions of numerous teams participating in global competitions such as the DARPA Subterranean Challenge, which advanced multirobot strategies for mine exploration (T. H. Chung et al., 2023), and the European Student AUV competition, which resulted with the conception and development of the SPARUS-AUV (Carreras et al., 2018). Significant contributions from individual developers include the highly configurable EspeleoRobô platform (Azpúrua et al., 2021), the self-driving patrol robot, presented in Figure 2.2 F, developed by Kim and Choi, 2023, the amphibious subterranean robot (Maity and Majumder, 2014), the buoyant crawler (Martz et al., 2020), and the unmanned surface vehicle roboboat (Villarroel et al., 2024) designed for partially flooded mines.

Multi-Robot systems

The development of multi-robot systems for exploring underground mining environments represents a significant advancement in mining technology, enhancing both safety and efficiency. From 2018 to 2021, the field gained significant interest thanks to DARPA's Subterranean (SubT) Challenge (Rouček et al., 2020b), aimed at deploying autonomous robotic teams to quickly map, navigate, search and operate complex subterranean settings such as man-made tunnels, urban undergrounds and natural cave systems (T. H. Chung et al., 2023). The challenge assembled teams from leading universities and research institutions worldwide to create multi-robot systems for navigating, reconstructing environments, and searching for objects in underground settings. Teams used various locomotion platforms, including legged, tracked, and wheeled terrestrial robots, along with various aerial vehicle configurations and some exceptional hybrid platforms. Among the competing teams in the final event, i.e. the event involving an underground cave complex, the best performing solutions are briefly commented: CERBERUS, CSIRO Data61, CoSTAR, CTU-CRAS-Norlab, Explorer, and MARBLE. For a comprehensive analysis of the SubT Challenge and the participating teams, readers should refer to T. H. Chung et al., 2023, which offers an extensive overview of the event. Additionally, DARPA's repository[1] compiles all related publications to the competition, providing detailed descriptions of each team's solutions for the various events throughout the competition.

[1] https://github.com/subtchallenge/subt_resources

Figure 2.3: Underground mining robot systems for surveying tasks, specifically teams competing in DARPA SubT Challenge. (**A**) CERBERUS team (Tranzatto, Mascarich, et al., 2022). (**B**) CSIRO Data61 team (Hudson et al., 2022). (**C**) MARBLE team (Ohradzansky et al., 2022). (**D**) Explorer team (Cao et al., 2023). (**E**) CoSTAR team (Agha et al., 2021). (**F**) CTU-CRAS-Norlab team (Rouček et al., 2020a).

Team CERBERUS (CollaborativE walking & flying RoBots for autonomous ExploRation in Underground Settings), the overall winner of the challenge, was formed through an international collaboration, including the Autonomous Robots Lab (University of Nevada, Reno), Robotic Systems Lab (ETH Zurich), Autonomous Systems Lab (ETH Zurich), HiPeR Lab (University of California, Berkeley), the Dynamic Robot Systems Group (University of Oxford), Flyability, and Sierra Nevada Corporation. To facilitate autonomous exploration of underground environments, the CERBERUS team focused on multimodal and multirobot perception, as well as path planning for exploration and area search. They developed a unified complementary on-board perception system that integrates LiDAR, cameras, and inertial sensor data. The robotic system deployed by the team (Figure 2.3 A) includes legged, wheeled, and aerial robots. The team developed and deployed a group of legged robots specifically designed for underground operations. These robots

are based on the ANYbotics ANYmal B300 (Hutter et al., 2016) series quadruped and feature several hardware and software modifications to form a specialized subterranean version: the ANYmal B SubT platform. CERBERUS also developed and deployed a team of "Aerial Scouts" to enable rapid exploration, particularly in areas of the course that were inaccessible to ground robots. Four different platforms (Alpha, Bravo, Charlie, Gagarin) were developed and deployed at various stages of the competition (See Section 2.1.2.3). In addition to the legged and aerial platforms, CERBERUS team also deployed a roving robot named Armadillo, based on Inspectorbots Super Mega Bot (SMB), to setup a high-gain communications antenna and carry large payloads and sensors (Tranzatto, Mascarich, et al., 2022; Tranzatto, Miki, et al., 2022).

Team CSIRO Data61, a collaboration between CSIRO, Emesent, and the Georgia Institute of Technology, secured second place in the challenge, narrowly missing out to CERBERUS. The CSIRO Data61 team (Figure 2.3 B) utilized a diverse array of quadrotor UAVs (developed by Emesent), tracked, and legged UGVs, all equipped with uniform sensing capabilities. Each robot in the team was outfitted with a shared sensor module, named CatPack, which includes a spinning LiDAR and cameras, all leveraging CSIRO's Wildcat real-time multi-agent Simultaneous Localization and Mapping (SLAM) solution and a 3D frontier-based exploration algorithm (Ramezani et al., 2022). During the competition, the team swapped out some platforms based on the specific requirements of each mission and the operational environment. Initially, the CSIRO solution featured the custom-made Hexapod Bruce platform (Steindl et al., 2020) and the Ghost Robotics Vision 60 quadruped. These were later replaced by Boston Dynamic's Spot, which was equipped with the aforementioned CatPack sensor system. For tracked platforms, CSIRO customized a BIA5 All Terrain Robot (ATR) and developed a smaller platform with an adaptable track system called the Dynamic Tracked Robot (DTR). A more detailed description of the robots is presented in Section 2.1.2.1. The UAV system comprised a DJI M210 UAV, equipped with an Emesent Hovermap payload, a custom gimballed camera system, and a Rajant radio. The Hovermap payload is a commercial product that runs Emesent's autonomy stack with additional features to facilitate integration with the rest of the CSIRO Data61 Team's system and to provide perception capabilities. Typically, the drone was deployed from the BIA5 ATR in scenarios where the robot could not access certain areas (Hudson et al., 2022).

Team MARBLE (Multi-agent Autonomy with Radar-based Localization for Exploration), composed of the University of Colorado Boulder, University of Colorado Denver, Scientific Systems Company, and University of California Santa Cruz, secured third place with their multirobot team variant. Like all high-performing teams in the competition, MARBLE's solution (Figure 2.3 C) used autonomous wheeled and legged platforms. For the ground platforms, the team chose to equip a Clearpath Husky and a Boston Dynamics Spot. The Husky has demonstrated its effectiveness as a motion base, as can be seen in section 2.1.2.1. Both ground platforms are equipped with a variety of essential sensors for key processes such as localization, artifact detection, and obstacle avoidance. A modular perception suite was developed for both platforms, incorporating the Ouster OS1-64 LiDAR, a LORD Microstrain 3DM-GX5-15 VRU, FLIR Gig E cameras, and a 5W dimmable LED. Each system features a custom power system that allows for a switch from a wired shore power supply to the onboard computer batteries. This setup improves the efficient use of the batteries onboard, which are a limiting factor in the duration of field testing deployments. For communications, Team MARBLE created custom communication beacons to augment their custom multirobot coordination solution. This enables the robots to share information with the base station and other robots in the

field. Each Husky platform can carry six beacons, each equipped with a single 2W Doodlelabs 802.11n radio (Biggie et al., 2023; Ohradzansky et al., 2022).

Team Explorer, formed through a collaboration between Carnegie Mellon University and Oregon State University, secured fourth place. They could have ranked in the top 3 if not for significant issues during the final event. The team's multirobot system featured custom-built wheeled platforms, commercially available legged platforms, and a combination of custom and commercial aerial vehicles (Figure 2.3 D). The decision to develop custom wheeled platforms (R1, R2, and R3) was driven by the challenges of subterranean environments specified in the competition guidelines. Drawing from past experiences, the team aimed for platforms featuring large diameter wheels and body articulation (pivoting) to enhance mobility, as well as a modular architecture to accelerate the development and debugging tasks. The ground robots have some distinctions. Specifically, R1 has a fixed chassis without suspension, while R2 and R3 were built with a centerline pivot to help the UGVs navigate obstacles and maintain better ground contact. Each ground robot is equipped with a perception payload and a communications node dropper. Additionally, R1 and R2 feature platforms for carrying and securing drones. Detailed descriptions of these robots are available in Section 2.1.2.1. For legged platforms, the team chose a Boston Dynamics Spot robot, enhanced with a custom perception suite. Similarly, for aerial vehicles, the team developed three custom quadcopters (DS1, DS3, DS4) and modified a commercially available quadcopter (Canary) (Cao et al., 2023; Scherer et al., 2022). Further details on the Explorer team's custom quadcopters can be found in Section 2.1.2.3.

Team CoSTAR, a joint effort between NASA Jet Propulsion Laboratory, California Institute of Technology, Masachussets Institue of Technology (MIT), Korea Advanced Institute of Science & Technology (KAIST) and Lulea University of Technology, finished in fifth place. The team developed a heterogeneous fleet of legged, wheeled, hybrid wheeled/tracked, aerial, and hybrid terrestrial/aerial robots (Figure 2.3 E). Their approach was based on an uncertainty-aware autonomy framework, dubbed NEBULA, which constructed the belief space over the robot and world states and performed reasoning and planning in that belief space. Similarly to other teams, the CoSTAR team decided to equip commercially available platforms, such as Spot and Husky robots, as well as custom-made aerial platforms with their custom-made sensor stack (Agha et al., 2021). As a differentiation aspect, CoSTAR deployed customized versions of commercial hybrid wheel / track platforms (see Section 2.1.2.1) and custom-made hybrid aerial/terrestrial platforms (see Section 2.1.2.4).

Lastly, Team CTU-CRAS-NORLAB, consisting of Czech Technological University and Université Laval, achieved sixth place. The team diverse multi-robot exploration system (Figure 2.3 F) included Husky wheeled robots, Absolem and Superdroid HD2 tracked robots, Boston Dynamics Spot and custom SCARAB II legged robots, PhantomX Mark II and HEBI robotics LiLy crawling hexapods, as well as custom aerial platforms. The team mapping solution utilized a variant of the Iterative Closest Point (ICP) algorithm. For exploration, both UAV and UGV platforms employed a frontier-based exploration strategy. In addition, three different communication systems were used: short-range link (WiFi), mid-range link (Mobilicom mesh network), and long-range link (droppable "Mote" modules) (Rouček et al., 2020a). Detailed descriptions of their Absolem and custom aerial vehicles can be found in Sections 2.1.2.1 and 2.1.2.3, respectively.

2.1.1.2 Mine rescue robots

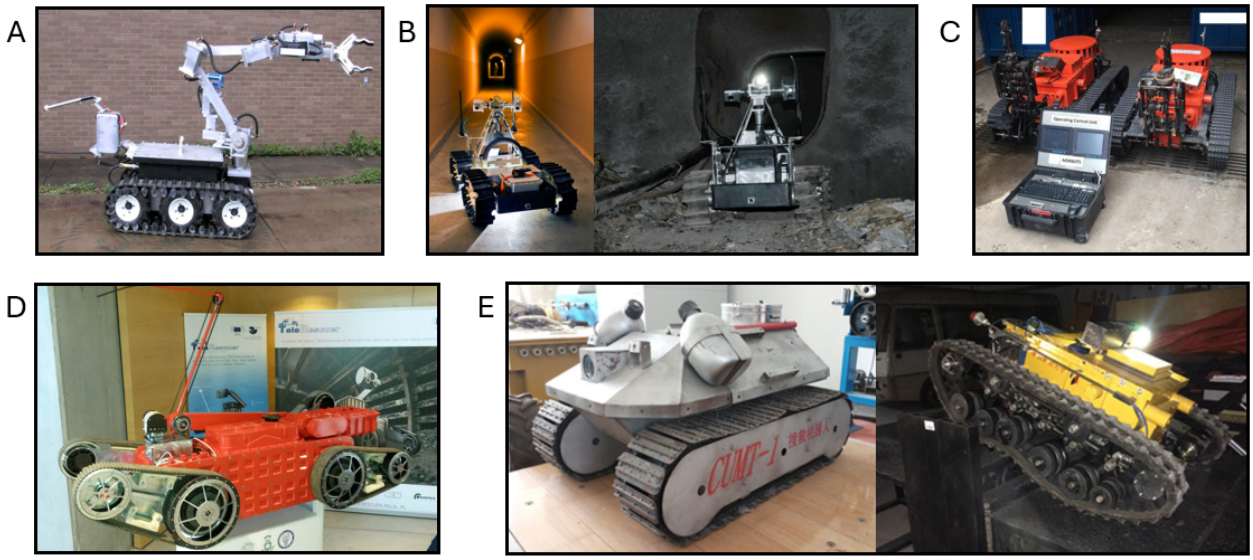


Figure 2.4: Mine rescue robot examples. (**A**) ANDROS Wolverine V2 (Reddy et al., 2015). (**B**) Gemini Scout (Dodge, 2020). (**C**) MSRBOTS multi-robot system (J. Zhao et al., 2017). (**D**) Telerescuer (Novák et al., 2018). (**E**) CUMT-I and CUMT-V mine rescue robots (Y. Li et al., 2020).

Mine rescue robots are invaluable assets in underground mining scenarios due to their ability to navigate hazardous environments and perform life-saving tasks in the event of emergencies. Although these platforms are usually used in case of an accident, it is important to highlight the potential of the platforms to operate in even more challenging conditions. Typically, mine search and rescue robots feature explosion-resistant structures, adaptable locomotion for varied terrain, gas sensors to assess mine conditions, and communication systems to link rescue teams with potential survivors. In the following, the most important developments and the main features of the solutions are presented.

Single-Robot solutions

The ANDROS Wolverine-V2 robot (Figure 2.4A), originally designed by Remotec Company for bomb disposal, was later repurposed for search and rescue tasks by the Mine Safety and Health Administration (MSHA). This 544 kilogram tracked robot features explosion-proof motors, surveillance cameras, lighting, atmospheric detectors, night vision, two-way voice communication, and a manipulator arm. It communicates with the surface via optical cables, capable of transmitting up to 1.5 km. However, its substantial weight hinders its operation in muddy or sludgy conditions, and its inability to navigate over dams and blockages significantly restricts its functionality.

The Gemini-Scout Mine Rescue Robot, depicted in Figure 2.4 B, is a robotic first responder created by Sandia National Laboratories with funding from the National Institute of Occupational Safety and Health (NIOSH) (Dodge, 2020). This unmanned ground vehicle is designed for entry into potentially hazardous areas to conduct explorations, assessments, and evaluations of dangerous conditions that may confront first responders during rescue operations. The robot is approximately 0.6 m tall and 1.2

m long and is equipped with gas sensors and a thermal camera to detect survivors, alongside a pan-tilt camera for obstacle identification. Continuously sends gas monitoring data, color images, and stereo camera depth information wirelessly to the operator. Its articulated structure and rubber tracks enable the Gemini-Scout to navigate stairs, negotiate through gravel and sand pits, rotate on the spot, and manage 45-degree slopes with minimal difficulty. Moreover, it is sufficiently light to maneuver over boulders and debris, but robust enough to withstand the underground pressures(Callow, 2018).

The Telerescuer, developed by Universidad Carlos III de Madrid, is a robot designed for teleoperated search and rescue missions. Shown in Figure 2.4D, the robot consists of a primary chassis weighing 590 kg, equipped with four individual tracked arms and a robust, explosion-proof housing that protects its motors, motor controllers, batteries, and central control system. It features a sensory arm that houses a sensory head, a 3D laser scanner, and a compact system to deploy Wi-Fi repeater modules. The sensory head, a cylindrical unit with an explosion-proof shell, contains five cameras (two for 3D imaging, one for broad site surveys, one for rear views, and a thermal camera), LED lighting, various gas detection sensors, and an inertial measurement unit (IMU). Telerescuer has been tested under both simulated and actual conditions, including at the Queen Luiza training coal mine in Zabrze, Poland (Novák et al., 2018).

Multi-robot solutions

The development of multi-robot search and rescue solution has been less explored in the literature. However, two notable developments can be highlighted. The Multi Search-and-Rescue (MSRBOTS) robotic system, presented in Figure 2.4 C, includes two tracked robots, each with a manipulator capable of clearing obstacles such as cables and steel rolled bars, along with a common operating control unit (OCU). Designed for use in subterranean coal mine settings, these robotic platforms weigh 430 kg and have dimensions of $1.315 \times 0.536 \times 0.862$ m. They possess an operational autonomy of 8 hours, are capable of collecting 10 different types of environmental data, and can send this information back to the OCU via a 1 km long fiber optic cable (J. Zhao et al., 2017).

Another notable example is the development of the coal mine rescue robots by the China University of Mining Technology (CUMT). Initiated in 2004, the first model, CUMT-I, was launched in 2006. CUMT-I (Figure 2.4 E left) featured basic remote control capabilities, video transmission, a variety of sensors for environmental data collection, and the ability to transport emergency supplies to accident sites. Despite its promising potential, it required additional improvements to meet the demands of actual search and rescue operations (Y. Wang et al., 2018). Consequently, following four more iterations, the most recent model, CUMT-V, was introduced in 2016. This model, an explosion-proof multi-drive crawler platform weighing 450 kg, is equipped with an infrared camera, an intrinsically safe audio system, microphone, and a CD10 multiparameter (10 parameters) gas sensor that satisfies the environmental detection requirements of search and rescue missions. In 2016, CUMT-V was tested in a rescue operation at the Ta Shan Coal Mine of the Datong Coal Mine Group, deploying three environmental detection robots, two rescue robots, and one firefighting robot. This test confirmed the robots' functionality and performance, including their ability to navigate underground, maintain communication, and successfully activate fire suppression systems at the site of a fire (Y. Li et al., 2020).

2.1.1.3 Excavation Robots

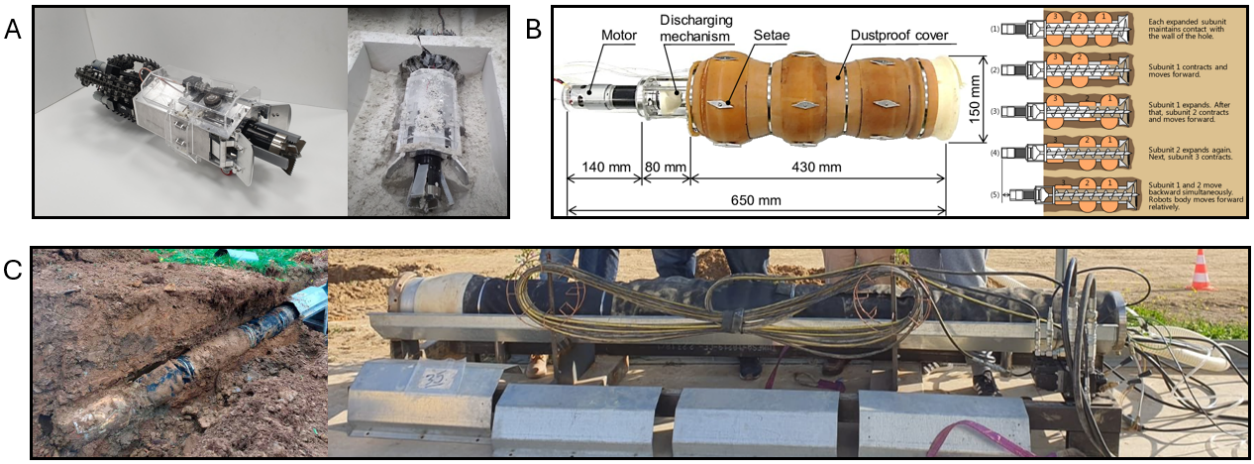


Figure 2.5: Underground excavation robot examples. (**A**) Molebot multitracked prototype (Lee et al., 2023). (**B**) Seabed excavation Robot SEAVO (Isaka et al., 2019). (**C**) Badger tunneling robot (Vartholomeos et al., 2021).

Excavation robots and drilling techniques are used in various sectors, including resource extraction and foundation construction. Research has been extensively carried out to improve drilling efficiency in both hard and deep areas. However, such conditions require the use of large and bulky equipment, and the soil removed is managed with mud and slurry, leading to environmental concerns related to the drilling fluids. This section reviews various research platforms for excavation tasks and the methods used to accomplish their mission, explicitly excluding the consideration of modifications to existing underground mining equipment with control systems that enable platform automation. For a more comprehensive analysis of the latest developments in excavation robots, particularly those designed to dig in the planetary regolith, it is recommended to consult the survey presented in Hongyu et al., 2021.

Mole-Bot, a remarkable excavation platform, is a biomimetic drilling robot developed by the Korea Advanced Institute of Science & Technology (KAIST). This robot inspired by moles has a diameter of 25cm, a length of 84cm, weighs 26 kg, and includes modules for drilling, debris removal, maneuvering, and propulsion. Its drilling module mimics the dental structure of mole rats. After excavation, it uses its forelimbs to remove soil and debris (Figure 2.5 A right). A feature inspired by the scapula of the European mole, embedded in the robot, transforms linear motion into a significant rotational force. Its elongated waist can rotate 360 °, similar to living mammals. The robot propulsion system has transitioned from an original wheel-based locomotion mechanism to a multi-track locomotion system in its most recent model(Figure 2.5 A left). For subterranean navigation capabilities, the team introduced novel sensor technologies and algorithms to determine the robot's location and direction using a graph-based 3D Simultaneous Localization and Mapping (SLAM) system that aligns with the sequences of the Earth's magnetic field, facilitating autonomous 3D navigation below the surface (Lee et al., 2019). The Mole-Bot is expected to be deployed in space exploration and the extraction of subterranean assets such as coalbed methane and rare earth minerals, requiring sophisticated drilling solutions in complex settings (Lee et al., 2020, 2023).

The LEAVO compact digging robot is an earthworm-inspired platform designed to achieve two main goals: 1) to drill a borehole for placing an environmental monitoring sensor and 2) to retrieve subsurface lunar samples from a specified layer. LEAVO's design is highly specialized, consisting of three main components: an excavation unit, a propulsion unit, and a discharging unit. The excavation unit features an earth auger drill and a casing pipe that excavates and transports soil through the pipe within the robot. The propulsion unit, composed of three segments that elongate and compress, mimics the peristaltic motion of an earthworm, allowing the robot to advance without being hindered by external soil pressure. This design also allows it to move actively, making it capable of functioning without relying on gravitational forces. The discharge unit is tasked with removing the soil displaced by the excavation unit out of the borehole (Fujiwara et al., 2018; WATANABE et al., 2021). In 2019, the robot was upgraded to SEAVO II (Figure 2.5 B) , an earthworm-inspired robot designed for seafloor exploration and sample collection. Due to the constraints of the experimental setup, SEAVO II has only achieved a burrowing depth of 430 mm in 54 minutes (Isaka et al., 2019).

Another example worth noting is the RoBot for Autonomous unDerGround trenchless opERations, mapping and navigation (BADGER). This mole-type drilling robot developed by the BADGER[2] European Consortium is an autonomous subterranean robotic system that can drill, maneuver, locate, map, and navigate in underground spaces, while allowing the construction of underground tunneling infrastructure. The robot is made up of four main modules: the bore head, the service modules, the joint modules, and the tunnel wall support. The bore head consists of four primary parts: a scraper plate, a suction pipe for removing excavated material, a hydraulically powered driving system, and radar antennas for detecting objects around the bore head. The joint modules consist of a steel hollow cylinder and house six actuators. Three of these actuators are in charge of producing movement, while the remaining three create a Stewart-like actuated joint that enables the robot to be directed at particular pitch and yaw angles. Each service module features a clamping mechanism, which includes airbags that inflate and deflate to offer anchor points for the joint modules to push against. The coordinated function of the clamping mechanisms and the joint modules results in a worm-like motion. These clamping mechanisms also counteract the torque generated during drilling and prevent rolling motion. The final module is the tunnel wall support, which coats the walls of the drilled bore with an additive material (such as resin) to form the pipe wall support(Vartholomeos et al., 2021).

2.1.1.4 Future Research Directions and Open Challenges

In recent years, a small yet dynamic community of researchers and practitioners, along with various industry players, has tackled the challenges of underground mine exploration, inspection, and mapping. Global initiatives, such as DARPA's SubT challenge, have highlighted the effectiveness of multi-robot strategies in unstructured underground settings. Utilizing diverse teams of robots that operate and collaborate concurrently has been shown to be a more efficient and resilient method for underground exploration tasks. Throughout the competition, the teams illustrated the advantages of modularity by creating modular perception units, which reduced the time needed for development, integration, and debugging. These autonomous robots, equipped with industrial-grade sensors and communication systems, were able to traverse hazardous and inaccessible areas, thus decreasing the necessity of human presence in dangerous conditions and providing a more robust solution through

[2] https://www.badger-robotics.eu/

the coordination and integration of various platforms. However, as the number and diversity of agents working simultaneously in the mine increase, managing these solutions becomes progressively more complex.

In the context of mine rescue operations, there is a clear trade-off between robustness and versatility, since the conditions faced by these robots are generally even more complex by nature. With platforms weighing around 400-600 kg due to the required reinforcements to withstand possible explosions during their operation, there is a distinct movement toward the adoption of ground-based platforms that utilize tracked and articulated mechanisms given their adaptability to unstructured terrains while maintaining a moderate consumption of energy to move larger payloads. Another common feature is the incorporation of manipulators into the robot's framework, primarily for debris removal.

The extreme conditions in underground mines present significant challenges in developing scalable and resilient autonomous solutions (Alexis, 2019). The inflexibility of current solutions to handle diverse tasks, coupled with the high cost of sensory systems and platforms, raises the question of whether smaller, multifunctional modular platforms with affordable and durable sensing technologies could be used in mining environments to autonomously carry out various tasks. By deploying these autonomous systems, human exposure to hazardous environments can be significantly minimized, reserving search and rescue robots for other potential scenarios in different settings. This approach requires further research on the development and deployment of such modular platforms to ensure that they can meet the demands of underground mining operations.

Robust autonomous solutions capable of performing material extraction in real mining environments have yet to be fully developed. However, scaled prototypes showcase technologies that could revolutionize the field, including innovative bioinspired solutions that offer new perspectives on mine architectures, locomotion methods within the mine structure, and selective mining strategies. Future research should focus on refining these prototypes and exploring the practical applications of bioinspired designs to create autonomous excavation platforms that can operate efficiently and safely in real-world mining environments.

Future research in the field of underground mine exploration, rescue operations, and excavation platforms must address the challenges of design complexity, scalability, and resilience. By focusing on the integration of multi-robot strategies, modular perception units, and innovative bioinspired solutions, researchers can develop more adaptable and robust systems. These advancements will not only improve the efficiency and safety of mining operations, but also reduce human exposure to hazardous environments. Continued collaboration between researchers, practitioners, and industry players will be essential in driving the development of these advanced autonomous systems and ensuring their successful deployment in real-world scenarios.

2.1.2 Locomotion methods of subterranean robots

Another commonly used classification approach for subterranean robotic platforms involves examining the primary locomotion methods. Mines exhibit a diverse range of layouts, including environments like dry and muddy terrains, narrow passages, accumulations of rocks and debris, steep slopes and cliffs, as well as partially flooded tunnels and areas. Consequently, robotic systems designed for these settings often feature a variety of locomotion methods. These systems range from terrestrial platforms with specialized locomotion techniques to aerial and aquatic systems, including

hybrid configurations. Figure 2.6 presents how these platforms can be classified according to their locomotion methods. In the subsequent section, an overview of the most prominent examples for each locomotion type is provided, along with a discussion on their accomplishments and potential future advancements.

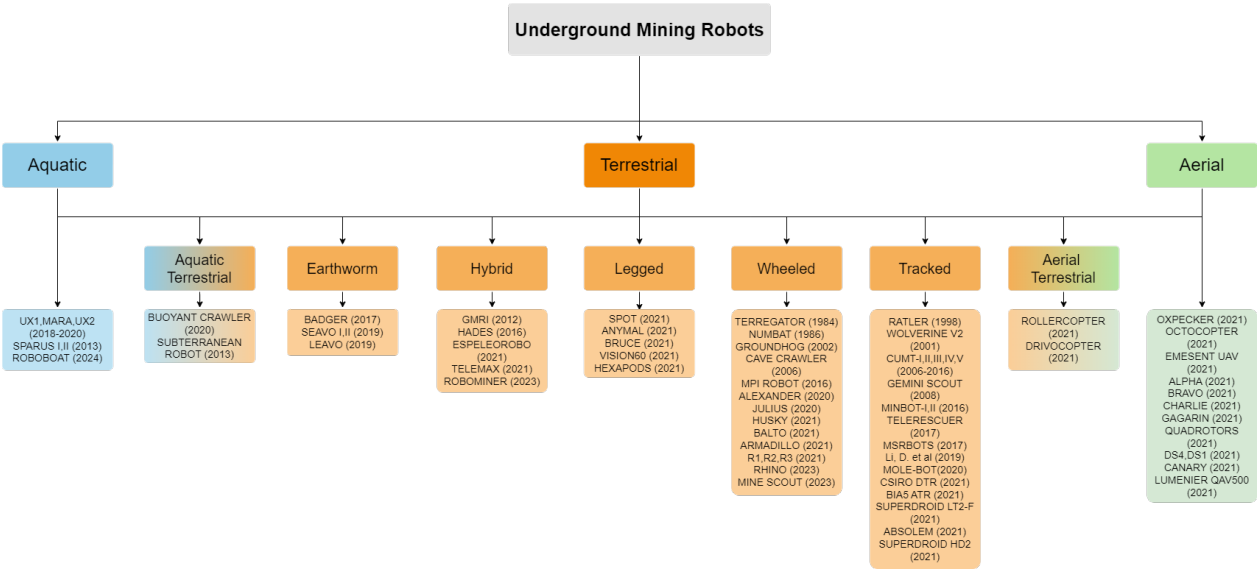


Figure 2.6: Underground mining robots classified according to the locomotion capabilities

2.1.2.1 Terrestrial

Various locomotion techniques have been devised for operating robots in subterranean mining environments, with terrestrial methods being the most prevalent due to their straightforwardness, versatility, independence, and energy efficiency for moving heavier platforms. Typically, ground locomotion techniques are divided into three primary categories: Wheeled, Tracked, and Legged. These categories encompass most advancements in robotic platforms. Methods that integrate locomotion techniques from the aforementioned categories are generally termed hybrid (Bruzzone and Quaglia, 2012). Additionally, other noteworthy locomotion methods, due to their relevance to the topic despite being application-specific, include earthworm locomotion methods. In the subsequent section, significant instances of each locomotion method are showcased and explained.

Tracked

Tracked wheel mobile robots have gained significant popularity in industries such as military, agriculture, and construction due to their outstanding mobility and capability to traverse off-road terrains. As a result, they are particularly effective for tasks related to reconnaissance and exploration. Track wheels offer excellent traction, allowing operation in various subterranean settings, including steep inclines and rough terrain, while reducing slippage risks (Wong and Huang, 2006). In addition, tracks facilitate uniform weight distribution, reduce ground pressure, and minimize damage to delicate underground structures, making them more suitable for use in such settings. Consequently, this locomotion technique is commonly adopted in the design of terrestrial subterranean robots.

Track configurations are categorized based on the count and arrangement of tracks, with robots typically featuring either articulated or non-articulated tracks. When the relative movement of the tracks is controlled using flippers, such robots are termed leg-track hybrid robots (Bruzzone and Quaglia, 2012).

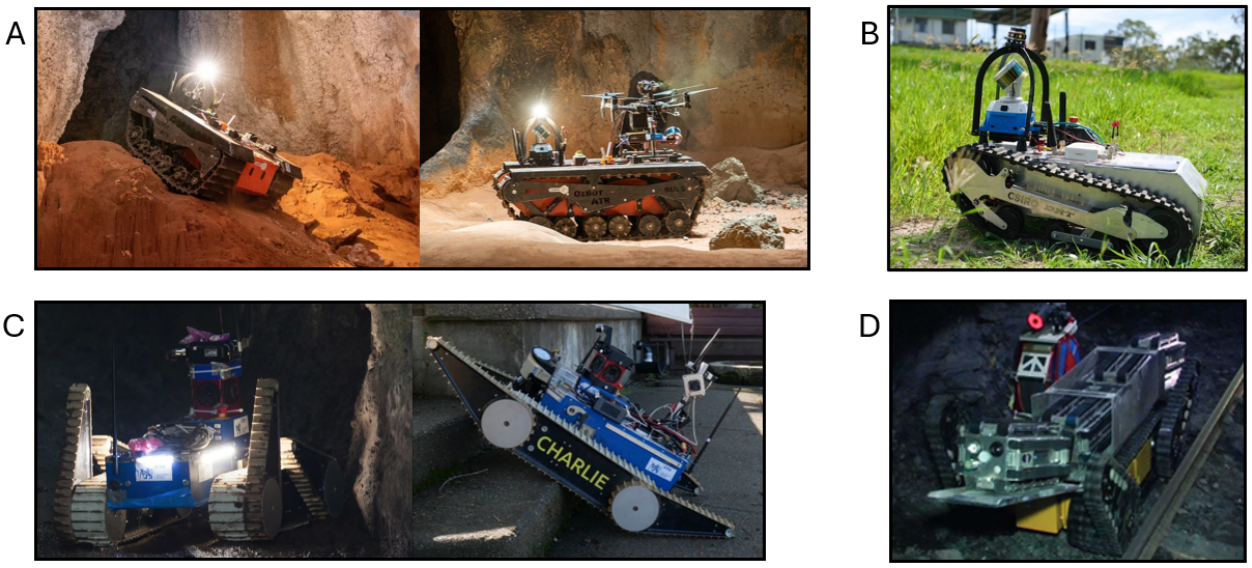


Figure 2.7: Examples of tracked underground mining robotic platforms. (**A**) CSIRO BIA5 All Terrain Robot (ATR) climbing a steeped slope (**right**) and serving as a marsupial platform to deploy UAVs (**left**) (Hudson et al., 2022). CSIRO Dynamic Tracked Robot (DTR) (Hudson et al., 2022). (**C**) CTU-CRAS-Norlab Absolem robot (Rouček et al., 2020a). (**D**) MINBOT-II mine rescue robot (W. Wang et al., 2017).

The BIA5 All Terrain Robot (ATR) (Figure 2.7A), developed by BIA5 and later modified by CSIRO for the DARPA SubT Challenge, is an UGV designed for mine exploration. This 90 kg, 1.4 m x 0.78 m robot can navigate various challenging terrains, including stairs and steep slopes up to 43 degrees. Its substantial ground clearance and large surface enabled the deployment of a communications network during competition events and even facilitated the in situ deployment of UAVs (Figure 2.7A left). In parallel, the Dynamic Tracked Robot (DTR) was designed to incorporate the advantages of the ATR platform into a more compact design (25 kg, measuring 0.8 m in length and 0.51 m in width), facilitating movement through tight doorways, stair climbing without flippers, and handling inclines up to 44 degrees. It also improves ground clearance and durability of the SuperDroid LT2-F base platform. As depicted in Figure 2.7B, the front track design resembles that of the ATR, allowing the robot to ascend steps and replicate the motion planning and behaviors of its larger counterparts. Furthermore, the suspension of the tracks is also designed in a way similar to that of the ATR to cushion the impact of falls (Hudson et al., 2022).

In the context of using articulated tracks to improve robot adaptability, a noticeable solution is the Absolem robot, utilized by the CTU-CRAS-Norlab team in DARPA's SubT Challenge. Manufactured by BlueBotics SA, this tracked robot (Figure 2.7C) was developed to navigate through terrains typical of disaster sites. It features two main tracks and four auxiliary flippers. The flippers are set by a custom controller, which takes the flipper position and data from mounted sensors to assess the

best setting for those flippers to help the robot traverse large obstacles such as stairs, curbs, and even gaps larger than the robot itself (Rouček et al., 2020a).

Another notable solution that uses articulated tracks is the mine rescue robot (MINBOT-II), developed by the Harbin Institute of Technology in China. Presented in Figure 2.7D, MINBOT-II employs a track-based movement mechanism with front and rear flippers. This configuration improves the robot's ability to efficiently modify its posture and overcome obstacles in challenging environments. Furthermore, the flippers are constructed with a modular design, which not only reduces the weight of the system, but also facilitates the assembly and disassembly processes from the main track-body, enabling diverse configurations (W. Wang et al., 2017).

Wheeled

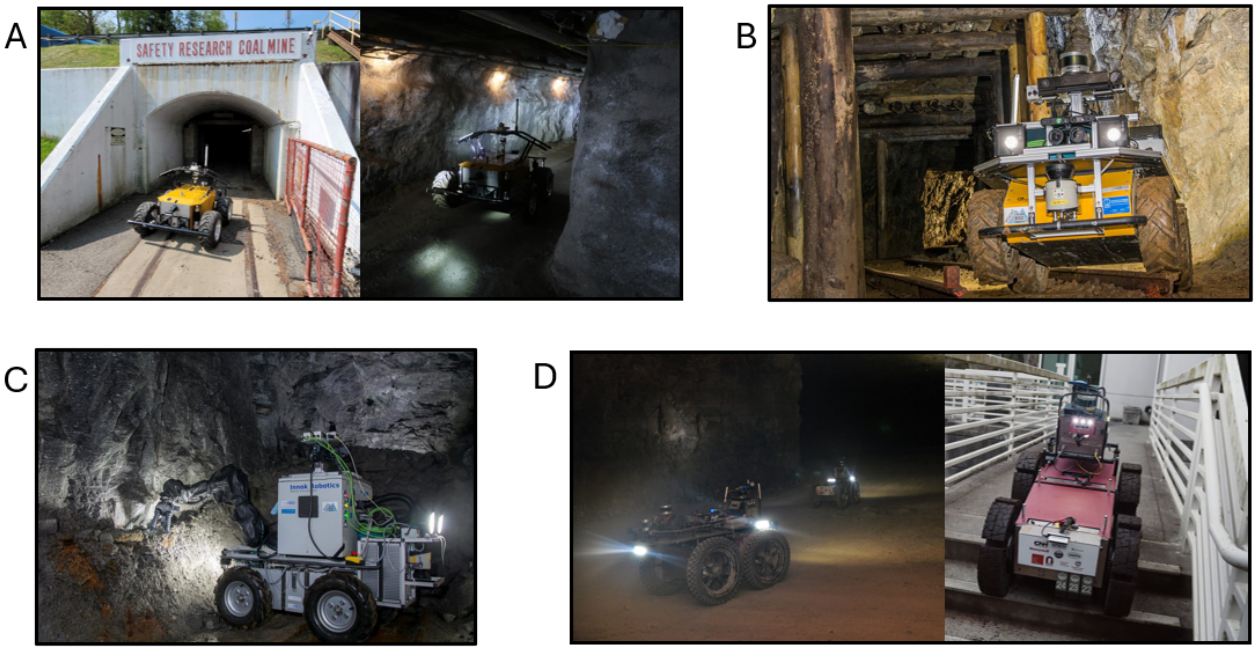


Figure 2.8: Examples of underground mining terrestrial platforms with Wheeled locomotion methods. (**A**) Rhino mine surveying platform (Tatsch et al., 2023). (**B**) Alexander autonomous mapping robot (Plotnikov et al., 2020). (**C**) Explorer SubT Challenge R1,R2,R3 mine robot explorers (Cao et al., 2023).(**D**) ARIDuA project Julius underground mining robot (Plotnikov et al., 2020).

Wheeled robots are commonly employed for mobility due to numerous benefits, such as straightforward design, energy efficiency, high velocity, and economical production costs (W. Chung and Iagnemma, 2016). Generally, wheeled robots can be classified according to the number of wheels and the steering mechanism used. Most robotic designs incorporate four or more wheels to improve stability, although three wheels are the basic requirement for static stability (Bruzzone and Quaglia, 2012). Regarding underground mining platforms, the majority of these platforms utilize a four-wheel configuration. However, there are exceptions documented in the literature, such as Terregator (Champeny-Bares et al., 1991) which employs six wheels, and Numbat (Ralston and Hainsworth, 1998) which uses eight wheels.

Rhino (Figure 2.8 A) is a custom-made four-wheeled UGV with a split-body chassis based on the skid-steer driving scheme developed for long-term autonomous operations in underground mines. The robot is also designed to carry a tethered drone, its winch system, and batteries as a payload, to extend the operational time of the UAV and inspect areas difficult to reach (Martinez et al., 2023). The Rhino robot is equipped with a set of sensors, including a ZED Stereo Camera, Ouster OS1-64 LiDAR, and an ADIS16495 Inertial Measurement Unit (IMU) to enable autonomous operation in underground environments. The robot computer onboard features an Intel i7-9700K computer with 32GB of RAM memory and a GTX 1050Ti GPU. The robot's ability to operate in subterranean environments was validated on multiple visits to the National Institute for Occupational Safety and Health (NIOSH) Safety Research Coal Mine, Pittsburgh, Pennsylvania (Tatsch et al., 2023).

The Alexander mine inspection platform (Figure 2.8 B), developed as part of the Mining-RoX research project, is focused on the regular production of mine maps and monitoring of underground environmental conditions. Alexander design is based on a Clearpath Robotics Husky A200 platform that features three laser scanners, two depth cameras, and two RGB cameras, along with a variety of environmental sensors such as anemometers, temperature and humidity sensors (Grehl et al., 2015). The Husky A200 platform weighs 50 kg, measures $67 \times 39 \times 99$ cm (width, height, length), and has an IP 55 classification. It can reach speeds up to 1 m/s, supports a maximum payload of 75 kg, and offers power lines of 5, 12, and 24 V. It should be noted that the Husky A200 robot has served as the base framework for numerous research platforms designed for mapping and inspection in underground settings, including its use by teams such as CoSTAR (Agha et al., 2021), CTU-CRAS-Norlab (Rouček et al., 2020a), and MARBLE (Ohradzansky et al., 2022) in the DARPA SubT Challenge.

Similarly to Alexander, Julius was developed by the ARIDuA project to explore the interaction between the Internet of Things (IoT) and robotics in a mining environment. Julius, shown in Figure 2.8 D), is adapted from an Innok Heros 444 platform, which includes four 16-inch wheels with odometer sensors, Velodyne VLP-16 and SICK LMS LiDARs, Kinect ONE RGB-D cameras, and a battery system capable of lasting up to 4 hours in an underground setting. Furthermore, the robot is equipped with an UR5 serial manipulator featuring a Robotiq gripper and an Asus Xtion camera mounted on the wrist. The manipulator is protected against water with a rubber cover. Julius weighs 138 kg and operates as a teleoperated platform with communication facilitated through Ethernet and a ROS driver (Plotnikov et al., 2020).

The mobile platforms R1, R2, and R3 (Figure 2.8 D) developed by the Explorer team to meet the requirements of the SubT challenge are three modular four-wheel platforms designed to traverse unstructured environments, such as staircases, minor debris, and inclined slopes. Adopting a modular design philosophy, the robots were equipped with a battery module, an electronics box (containing power and computing components), motor modules (each with a motor and motor controller, four per robot), and a sensor payload. The ground robots have some distinctions, The first version, R1, is 0.9 meters in width and 1 meter in height, featuring a fixed chassis without suspension and incorporating all the robotic modules. The second prototype introduces a centerline pivot suspension system, which enhances the robot's ability to overcome obstacles and maintain ground contact. Finally, the third platform is a smaller version, approximately 0.7 meters wide and 0.7 meters tall. This reduction in size affected the modularity of the robot, necessitating the integration of electronics into the robot structure while keeping the battery and motor modules to simplify mechanical and

electrical systems (Cao et al., 2023).

Legged

The introduction of legged robots into mining environments is a fairly recent development due to the complexity of their control systems and their autonomy limitations. Nevertheless, legged robots possess unique mobility features that make them ideal for navigating difficult terrains. In the DARPA SubT challenge, various teams created and deployed different legged robots to function in underground mining settings, thanks to their outstanding ability to navigate narrow and unstructured areas (Rouček et al., 2020b). The following section provides a description of the solutions employed.

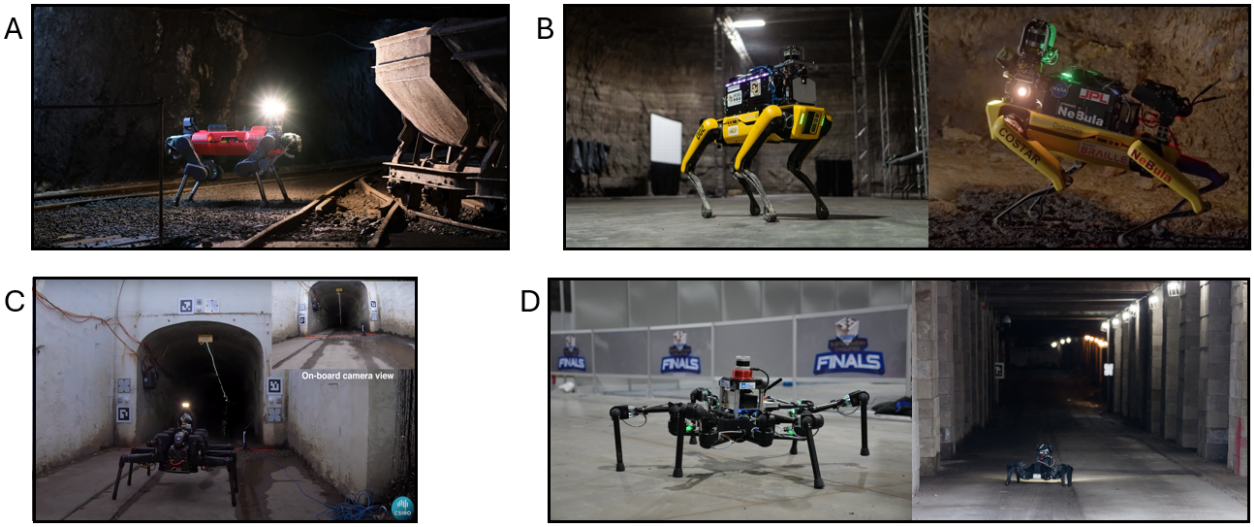


Figure 2.9: Examples of underground mining terrestrial platforms with biomimetic locomotion methods. (**A**) CERBERUS Anymal SubT Challenge version (Tranzatto, Mascarich, et al., 2022). (**B**) Boston dynamic Spot equipped with sensory system for Marble (**left**) and CoSTAR (**right**) teams competing in DARPA SubT challenge (Agha et al., 2021; Ohradzansky et al., 2022). (**C**) Csiro Data61 Bruce Hexapod Steindl et al., 2020 (Hudson et al., 2022). (**D**) CTU-CRAS-Norlab Legged robots: HEBI robotics Lily (**left**) and Scarab II crawling Hexapods (**right**) (Forouhar et al., 2021; Rouček et al., 2020a).

The CERBERUS team engineered and implemented a group of specialized legged robots designed for subterranean tasks. These robots, derived from the ANYbotics ANYmal B300 series quadruped (Hutter et al., 2016), underwent numerous modifications in both hardware and software to develop a tailored underground variant: the ANYmal B SubT model, presented in Figure 2.9A. The ANYbotics ANYmal B300 series is designed for resilience and agility, ideal for autonomous tasks requiring long durations in demanding conditions. It features three flexible joints per leg, equipped with electronic components that enhance torque control and impact resistance. Developed and optimized for over a decade, this line of quadrupeds excels in robustness, agility, and mobility, while maintaining a compact form and lightweight design, capable of operating for 1 to 2 hours. In addition, they also allow for omnidirectional locomotion, which is advantageous inside narrow environments.

Several other high-performing teams including CoSTAR, CSIRO, MARBLE, and EXPLORER opted to adapt Boston Dynamics's Spot robot with different sensor suites to suit their requirements. Spot's

factory perception package from Boston Dynamics comprises five custom RealSenses distributed around the robot. To enable higher levels of autonomy required in the SubT challenge, the teams augmented Spot's in-built sensing abilities by adding custom-made sensing packages, usually including LiDARs, RGBD and thermal Cameras, Led arrays, IMUs, WiFi anthenas, and other useful sensors in rigid and compact mechanical structures.

CSIRO developed a specialized Hexapod called *Bruce* to swiftly and autonomously navigate unknown underground environments. Bruce was engineered with most of its mass centralized in a single body, featuring very lightweight legs and high bandwidth task frame impedance for each leg. This design allows the system to react similarly to the spring-loaded inverted pendulum (SLIP) model, which effectively represents the dynamics of most legged robots and animals, including hexapods. Bruce achieves movement through finely tuned leg impedance feedback paired with an open loop gait engine similar to a central pattern generator (CPG). This approach ensures dynamic stability at increased velocities and allows for navigating uneven terrain without the need for explicit foot-ground contact detection. Bruce applies this principle to a leg with three degrees of freedom, which requires both passive and active software-regulated impedance control to maintain compliance (Steindl et al., 2020). Nevertheless, Bruce development was discontinued due to the complexity of the solution and was replaced by Boston Dynamic Spot (Hudson et al., 2022).

CTU-CRAS-Norlab deployed several legged robots, with a mix of commercially available adapted robots and custom-made ones. With respect to commercially available platforms, the team used Phantom X Mark II crawling Hexapods, HEBI Robotics Lily robot (Figure 2.10 D left) and several Boston Dynamics Spot, all equipped with the team's own sensor suite. Regarding custom-built platforms, the team created a small hexapod crawler named SCARAB II. The robot measures approximately 0.25 meters in length, 0.4 meters in width, and 0.25 meters in height when in its default stance, and weighs 4.7 kilograms. It can operate continuously for 1.5 hours. The robot's top speed is about 0.4 meters per second. An Intel NUC Core i7 provides the computational power necessary for locomotion control and executing high-level motion planning and decision-making algorithms. For environmental mapping, the robot uses an Intel RealSense D435 depth camera and a T265 tracking camera bundle. The XSens MTi-3 AHRS is used to estimate the robot's orientation. (Forouhar et al., 2021).

Earthworm

A less common locomotion method for underground mining robots is the biomimetic approach inspired by the peristaltic motion of earthworms. In peristaltic crawling, the earthworm generates a longitudinal wave from the anterior to the posterior of its body by contracting the muscles in each successive body segment, known as metameres (Nakamura et al., 2006). The drive mechanisms for peristaltic crawling robots encompass pneumatic, hydraulic, electric, magnetic, hybrid technologies, and other emerging methods such as optical, acoustic, or thermal techniques (Liu et al., 2023). Currently, robotic platforms that utilize this locomotion technique are designed for excavation tasks, primarily aimed at extracting samples from seabeds or extraterrestrial environments and assisting in tunnel creation for construction purposes, as detailed in Section 2.1.1.3.

Hybrid

The emergence of hybrid locomotion systems for underground mining platforms has garnered attention in recent years, as they are often considered the most versatile solutions for mobile robots. These systems combine the advantages of the main categories (wheels, tracks, legs) while aiming to reduce their drawbacks. Generally, these robots can be classified into four types based on the combination of locomotion methods: legs-wheels, legs-tracks, wheels-tracks, and legs-wheels-tracks (Bruzzone and Quaglia, 2012). This section highlights some notable examples designed for underground mining environments.

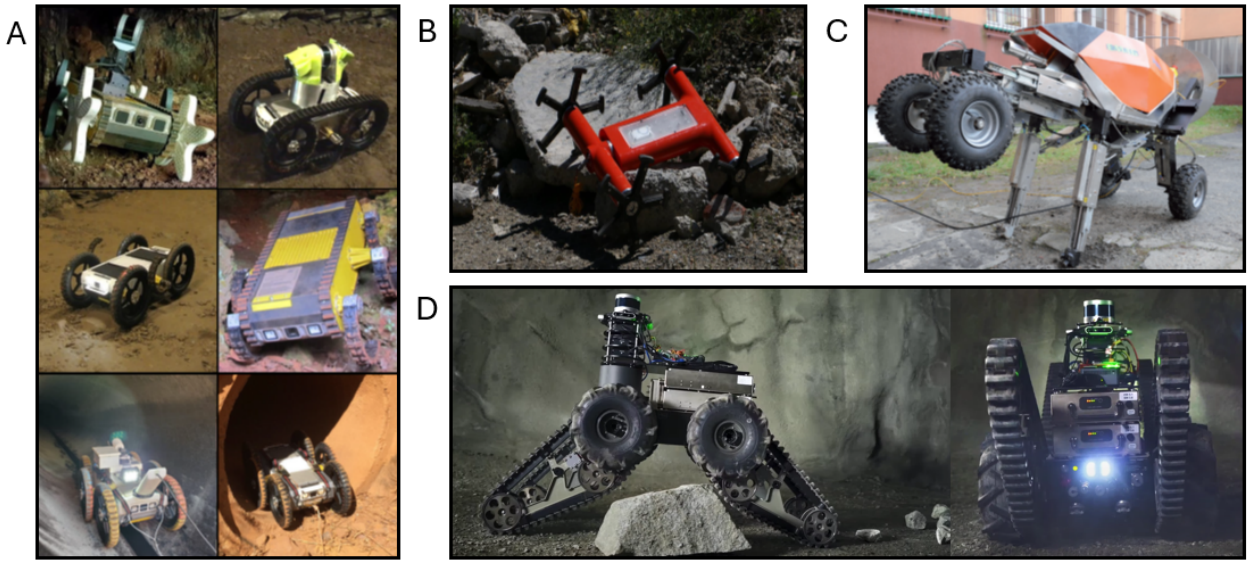


Figure 2.10: Examples of underground mining terrestrial platforms with hybrid locomotion methods. (**A**) Different configurations of EspeleoRobô (Azpúrua et al., 2021). (**B**) Spoked-Wheel locomotion method of HADES underground mine disaster scouting robot (Molyneaux, 2016). (**C**) GMRI Mine inspection platform featuring Wheels and legs acting as movable supports(Kasprzyczak et al., 2012). CoSTAR Telemax robot adapted for DARPA SubT Challenge (**D**) (Agha et al., 2021) .

A notable platform due to its configurable locomotion method is the EspeleoRobô (Figure 2.10 A), presented by Azpúrua et al., 2021, to inspect natural caves during teleoperated missions. The EspeleoRobô is a mobile robot with highly configurable locomotion mechanisms, including legs, wheels, and tracks, as well as all possible combinations of the aforementioned methods. The robot features 6 different motors where the different locomotion mechanisms can be manually replaced using a quick release pin technology. Regarding robot specifications, EspeleoRobô is water-resistant (IP67), presenting a payload capability of 50 % of its weight, ROS integration, and initial support for autonomous missions.

Regarding the integration of leg and wheel locomotion techniques, an exemplary case is HADES, an underground search and rescue robot developed by Molyneaux et al., 2015. Featured in Figure 2.10 B, this robot weighs 20 kg, measures $0.4 \times 0.6 \times 0.7$ m, has an operational time of 2.5 hours, and is equipped with a four spoked-wheel locomotion system featuring a passive pivot point for

the front and rear axles. The HADES locomotion system enables it to traverse minor debris while maneuvering through significant debris (such as machinery, collapsed beams, or wall/roof rubble). To meet explosion-proof requirements, HADES is equipped with a purging and pressurizing system for the robot chassis, avoiding the need for a heavier flame-proof chassis. The robot chassis, made from 2mm thick fiberglass, is designed to protect all electronic components while ensuring a high strength-to-weight ratio (Molyneaux, 2016).

Alternative solutions, such as GMRI, chose to incorporate legs that function as supports or pivot points to enhance the robot's maneuverability. Developed by the Institute of Innovative Technologies EMAG and the Industrial Research Institute for Automation and Measurement PIAP, GMRI (Figure 2.10 C) is a mobile inspection platform for mining, designed for explosive hazardous environments. This robotic vehicle is equipped with sensors to measure the concentrations of certain gases (CH4, CO, CO2, O2), cameras, a transmission system, control and visualization systems, and electrical accumulators. The robot's drive structure relies on a system of movable supports (legs) and features wheels—two widely spaced at the rear and two narrowly spaced at the front. The two legs are independently controlled pneumatic supports, operated via two-state valves connected to a compressed nitrogen tank, enabling the robot to adjust its height for better adaptability in rough terrain (Kasprzyczak et al., 2012).

Further advancements, such as the modified Telemax version by the CoSTAR team (Figure 2.10 D), integrate wheeled and articulated tracks into a unified platform. The Telemax Pro served as the foundational structure, with the manipulator removed, and a highly customized heterogeneous sensor suite, computing units, batteries, and speed controllers added. This system employs a 4 articulated-track drive mechanism, supplemented with wheels for additional traction, allowing it to navigate obstacles, gaps, and steep inclines with ease (Agha et al., 2021). Despite limited information disclosed by the team about the platform, the base unit weighs approximately 77 kg (including the manipulator) and can overcome obstacles up to 0.5 m in height and gaps up to 0.6 m in width.

2.1.2.2 Aquatic

For the exploration of flooded and partially flooded mines and underwater caves, several research projects have presented different solutions to explore and map confined spaces, where Autonomous Underwater Vehicles (AUVs) and Autonomous Surface Vehicles (ASVs) have been developed to address this challenge.

The Underwater Robotics Research Center (CIRS) of the University of Girona presented the SPARUS AUV (Figure 2.11B), a lightweight hovering vehicle with a mission-specific payload area and efficient hydrodynamics for long autonomy in shallow water (Carreras et al., 2013, 2018). The robot, originally conceived for the European Student AUV competition, has been tested in different underwater cave complexes in Spain, providing acoustic, optical, and inertial measurements for autonomous navigation research (Mallios et al., 2016).

Another remarkable solution for underwater mine exploration is the UX-1 robot (Martins et al., 2018) along with its upgraded versions MARA, UX-1NEO and UX-2Deep (Martins et al., 2020;

Pinto et al., 2020), which were developed within the framework of the UNEXMIN[3] and UNEXAP[4] projects. These compact spherical robots, presented in Figure 2.11C are equipped with a suite of advanced technology, including multibeam sonar, five digital cameras, and rotating laser line structured light systems. These features enable the robot to generate precise point clouds of their surroundings and capture high-resolution imagery. The UX robots were specifically designed for exploration in underwater mines and the collection of geological and topological data. Different field tests were conducted at various locations throughout Europe, which have validated the capabilities of these platforms (Zajzon et al., 2023).

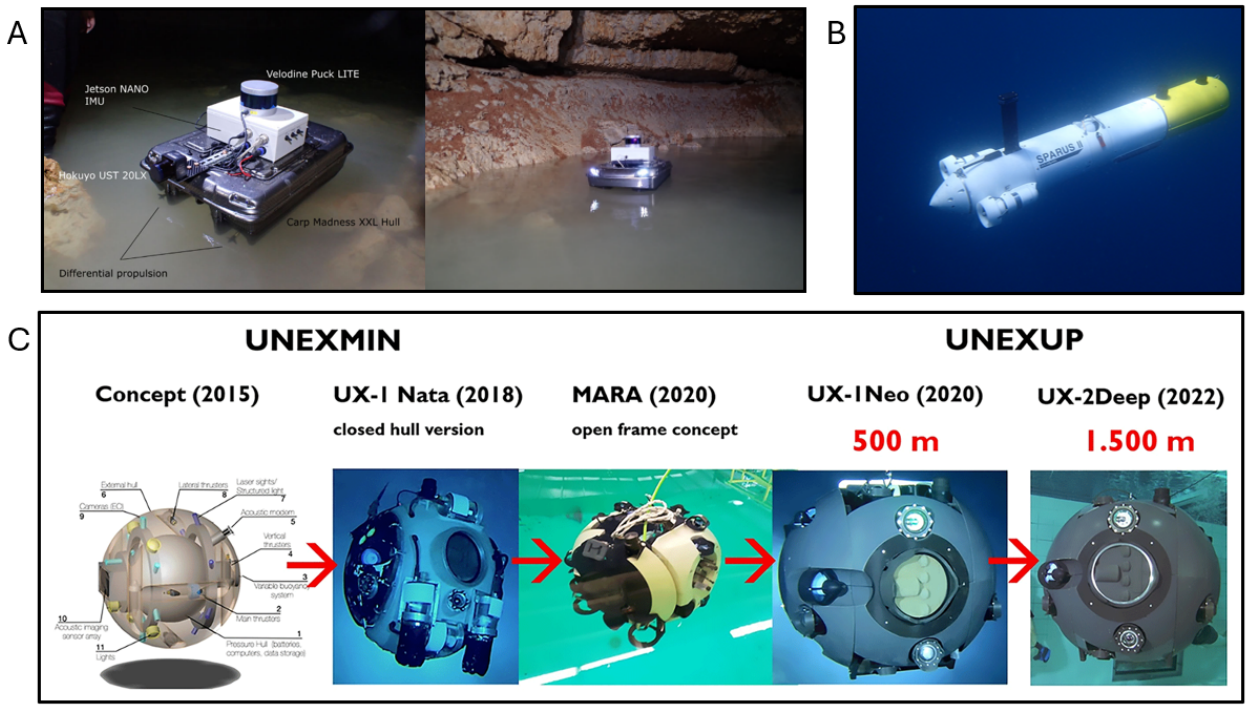


Figure 2.11: Examples of aquatic type mine exploring robots. (**A**) RoboBoat Villarroel et al., 2024. (**B**) Sparus-II AUV (Carreras et al., 2018). (**C**) Evolution of UX AUV robots during UNEXIN and UNEXUP projects (Pinto et al., 2020).

For partially flooded mines, an example worth noting is RoboBoat, developed by Villarroel et al., 2024. RoboBoat, shown in Figure 2.11A, consists of an unmanned surface vehicle designed to acquire three-dimensional (3D) point cloud representations of narrow flooded galleries in caves, mines, and other similar environments where conventional surveying and mapping procedures cannot be applied. The boat has differential propulsion provided by two propellers driven by two brushed motors with a speed regulator but without speed feedback.

2.1.2.3 Aerial

Unmanned aerial vehicles (UAVs) provide substantial benefits in difficult environments. Known for their ease of deployment, cost effectiveness and high adaptability, the use of UAVs for searching

[3] https://www.unexmin.eu/
[4] https://unexup.eu/

and exploring subterranean areas has gained traction in recent years. This section presents several pertinent examples of UAV implementation in mining contexts to illustrate the primary features and design characteristics. For a more detailed overview of UAVs in underground settings, interested readers should refer to He et al., 2024 survey.

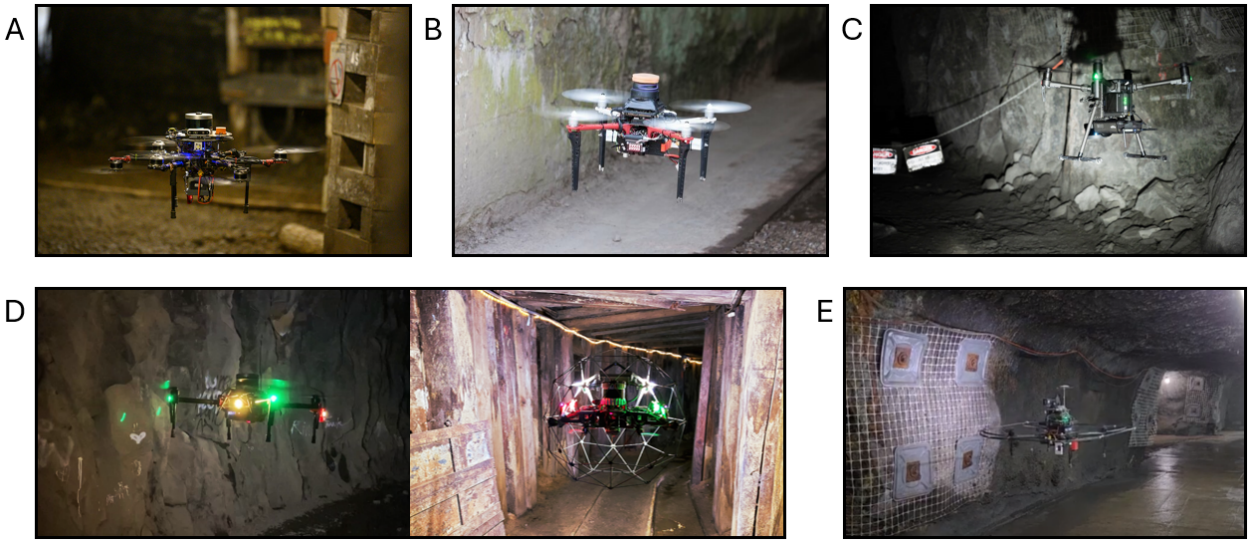


Figure 2.12: Examples of aerial robots that operates in underground mining environments. (**A**) Carnegie Mellon Explorer SubT custom built quadcopter (Cao et al., 2023). (**B**) CTU-CRAS-Norlab SubT custom Quadrotor (Rouček et al., 2020a). (**C**) Emesent UAV adapted by CSIRO SubT team (Hudson et al., 2022). (**D**) Alpha (**left**) and Gagarin (**right**) UAV for CERBERUS SubT Challenge (Tranzatto, Mascarich, et al., 2022). (**E**) Oxpecker inspecting a stone mine wall (Martinez et al., 2023).

Various designs of multirotor UAVs were developed and deployed by several teams in DARPA's SubT challenge. For the Explorer team, aerial vehicles were designed to traverse vertical shafts, steeply sloping passageways, staircases, and other obstacles that are intrinsically difficult to traverse for a ground-based robot. The team designed and deployed custom small drone platforms, shown in Figure 2.12A, featuring propeller guards that allowed the drone to bump into obstacles without compromising operation, as well as a battery and a robust sensory system including depth cameras and LiDARs. In addition to the small drones, the team opted to use additional drones built by Canary Aerospace (Cao et al., 2023). CTU-CRAS-Norlab team solution followed a similar approach to the Explorer team, including propeller guards. The drones developed by the team, shown in Figure 2.12B, used the DJI F450 kit as a baseline, controlled by an Intel® NUC onboard and the PixHawk autopilot, and featuring the RPLidar A3, two Bluefox RGB cameras with an LED illumination strip (Rouček et al., 2020a). The CSIRO team UAV system consists of a DJI M210 UAV (Figure 2.12 C), equipped with an Emesent Hovermap payload, a custom gimbal-mounted camera system and Rajant radio. The Hovermap payload is a commercial payload that runs Emesent's autonomy stack with additional functionality to facilitate integration with the rest of the team system (Hudson et al., 2022). Team CERBERUS developed and deployed a group of "Aerial Scouts" to enable swift exploration, particularly in areas of the course that ground robots couldn't reach. Three robots, named Alpha, Bravo, and Charlie (Figure2.12D left), use the DJI Matrice 100 quadrotor as their

base structure. For advanced processing tasks such as sensor data collection, localization, mapping, and planning, each robot is equipped with an Intel NUC Core-i7 computer (NUC7i7BNH), while an Intel Movidius Neural Compute Stick is employed for artifact detection. Another category of Aerial Scouts, named Gagarin (Figure 2.12D right), was developed to offer several unique features. This robot is built to navigate narrow and visually impaired environments. Gagarin is a drone encased in a collision-resistant cage that allows it to endure impacts with obstacles. This drone features a compact design with a tightly integrated, energy-efficient NVIDIA TX2 board with 6 ARM CPU cores and a 256-core NVIDIA Pascal GPU, an Ouster OS0 or OS1 (depending on the Gagarin model) LiDAR with a broad vertical FOV, an IMU, and two fisheye cameras, making it suitable for maneuvering through staircases and vertical shafts. In addition, Gagarin is equipped with a custom lighting system that includes LEDs positioned at various angles to minimize the impact of dust on the image, extend the visual range, and enhance the environment's texture (Tranzatto, Mascarich, et al., 2022; Tranzatto, Miki, et al., 2022).

Another noteworthy solution is the Oxpecker (Figure 2.12 E), a tethered unmanned aerial vehicle (TUAV) designed for assessing the structural integrity of underground stone mine pillars, developed by Martinez et al., 2023. This UAV is part of a multirobotic system that includes a UGV (Rhino). Since the Oxpecker's batteries are carried by the UGV and the tether provides relative measurements between the vehicles, this configuration not only enhances the drone's battery capacity but also enables navigation and landing without the need for vision. Regarding the robot's construction, the authors chose to use a Holybro X500 Frame Kit, combined with a Pixhawk 4 Flight controller unit, an Intel® NUC 11, and an Arduino UNO R3 for low-level sensor communication. In terms of sensors, the drone is equipped with an Intel® RealSense™ L515 solid-state LiDAR depth camera for mapping, an Intel® RealSense™ Tracking Camera T265, and a suite of sensors integrated into the tether to measure the drone's pose relative to the UGV.

2.1.2.4 Hybrid

The exploration of hybrid locomotion techniques for subterranean platforms has been relatively underexplored due to the complex nature of merging different transport means into one prototype. While certain multi-robot systems, like marsupial robots, can implement a combined locomotion strategy involving two distinct means, typically UGVs and UAVs, this section emphasizes solutions that can switch between two different means within a single platform. These solutions are categorized into terrestrial/aquatic and terrestrial/aerial platforms.

Aquatic/Terrestrial

For amphibious solutions, the subterranean robot (Figure 2.13 A) is found. The prototype is made up of a watertight compartment that encloses motors, the onboard battery pack, cameras, and other electronics. Two motors are responsible for driving the tracked wheels of the robot on the ground, whereas two other DC brushless thrusters are in charge of the robot locomotion system underwater. The thrusters are mounted on a specially designed tilt mechanism to provide the system with the ability to tilt up or down while floating (Maity and Majumder, 2014).

Another amphibious prototype worth noting is the 6x6 buoyant crawler (Figure 2.13 B) where six buoyant wheels provide the platform with a high payload capability in water, sludge, and rocky

terrain. Independent steering control on the front, middle, and rear wheels allows the robot to overcome a range of obstacles. The platform is teleoperated (Martz et al., 2020).

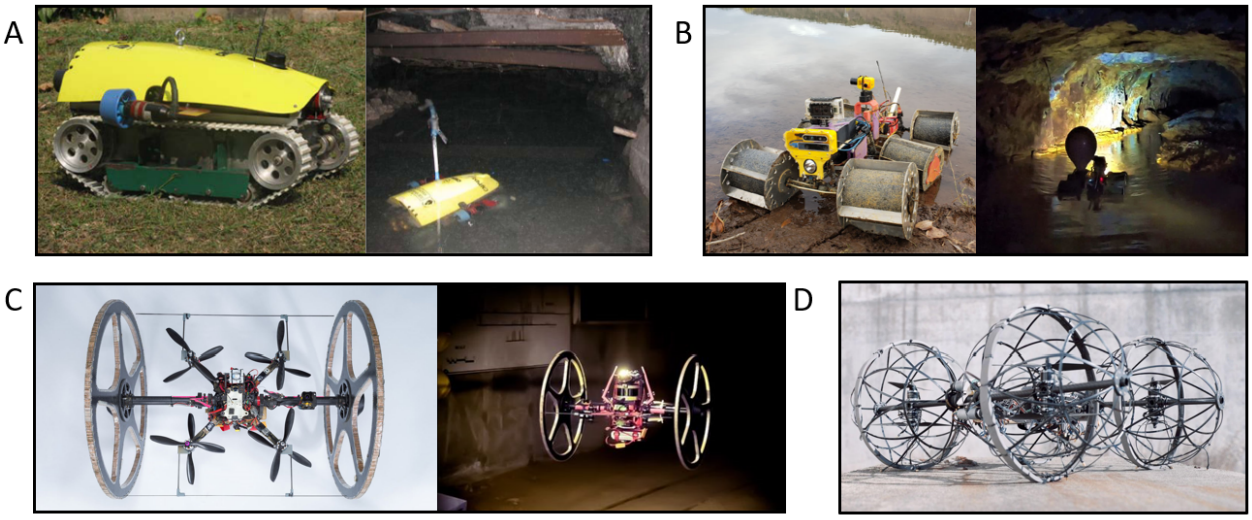


Figure 2.13: Examples of underground mining platforms with hybrid means of transportation. (**A**) Amphibian Sub-Terranean robot (Maity and Majumder, 2014). (**B**) Buoyant crawler (Martz et al., 2020). (**C**) Aerial/Terrestrial Rollocopter (Agha et al., 2021; Fan et al., 2019). (**D**) Aerial/Terrestrial Drivocopter (Agha et al., 2021; Kalantari et al., 2020).

Aerial/Terrestrial

Concerning hybrid aerial/ground platforms, two systems have been conceived and implemented in an underground mining environment. Both systems are part of an active research line of NASA's Jet Propulsion Laboratory (JPL). The Rollocopter is an exploration robot that combines aerial and passive ground locomotion mechanisms. This design extends the robot's range beyond that of purely aerial quadrotors and avoids the obstacle navigation challenges faced by ground-only robots. When the Rollocopter encounters an obstacle, it can simply fly over it. As shown in Figure 2.10D, the Rollocopter is built on a quadrotor base with two passive wheels. These wheels, attached to the drone via the main shaft, are constructed from a lightweight carbon fiber honeycomb structure. The vehicle is actuated by its propellers and uses the wheels for rolling, thus achieving hybrid mobility. The Rollocopter weighs 4.3 kg and is equipped with an Intel RGBD camera, Velodyne 360° VLP-16 LIDAR, IR LED-based height sensor, Pixhawk flight controller, motor encoders, and an Intel NUC for onboard computing (Fan et al., 2019). The CoSTAR team has successfully utilized the Rollocopter in the DARPA SubT challenge (Agha et al., 2021). A subsequent version of the Rollocopter is the Drivocopter (Figure 2.10C), also developed for the DARPA SubT Challenge. The primary advancement in this design is the independent control of both locomotion systems. The platform employs a quadrotor configuration for aerial movement, weighs 5 kg, and is driven by eight MN3110 T-motor brushless DC motors (KV700) with 9.5" x 4.5" propellers. It runs on a 6S, 10Ah lithium polymer battery pack, offering approximately 10 minutes of hovering time. For ground movement, four driven wheels, referred to as Actuated Propeller Cages (APC) by the authors, serve as propulsion system guards in case of crashes and are a unique design element. The construction involves cutting a flat 2mm thick Carbon Fiber sheet, bending it into a spherical shape, and securing

it with 3D printed nylon hubs. Maxon DCX16L (18V, 16 watts) brushed DC motors with a 243:1 gearset were chosen to drive the wheels. Power is transmitted to the wheels through GT3 2mm pitch timing belts, ensuring adequate torque and allowing the platform to reach a maximum speed of 1m/s (Kalantari et al., 2020).

2.1.2.5 Future Research Directions and Open Challenges

Ground robot locomotion systems are designed to meet specific criteria, including top speed, energy efficiency, and adaptability to unstructured environments. Wheeled robots generally outperform others in speed and energy efficiency, but they struggle with obstacle navigation compared to tracked or legged systems. Legged robots, despite their superior capability in traversing unstructured terrains, face significant challenges such as high energy consumption, increased complexity, limited payload capacity, and reduced autonomy. Tracked robots present a balanced alternative, offering better efficiency than legged robots and enhanced agility over wheeled robots (Ugenti et al., 2023). In addition, hybrid platforms, which integrate various primary locomotion methods like legs, wheels, and tracks into a single system, provide versatile solutions for land navigation. However, this integration adds complexity in terms of assembly and kinematic modeling. These hybrid mechanisms might feature interchangeable locomotion systems, combined wheel-leg configurations, or simultaneous use of tracks and wheels. Less common methods, such as earthworm locomotion systems, are typically utilized in platforms designed for excavation, where robots burrow into the ground. Currently, most platforms using these advanced locomotion methods are confined to construction, seabed inspection, or laboratory settings, with limited application in actual mining operations.

In recent years, multirotor UAVs have become increasingly popular in outdoor settings due to their cost-effectiveness and adaptability, finding applications in diverse sectors including commercial, social, and defense. However, subterranean settings pose distinct challenges for these UAVs, such as lack of GPS signal, narrow passages, and poor lighting. For successful missions, it is crucial that UAVs are both highly reliable and secure when operating in unknown territories. Significant research has been directed towards enhancing drone capabilities in autonomous exploration tasks by improving their environmental awareness. Additionally, the deployment of multi-modal systems and hybrid platforms can combine the strengths of different systems to enable enhanced mobility in diverse and challenging environments.

The introduction of marsupial robotic systems, which combine ground and aerial solutions, has resulted in versatile alternatives to increase the maneuverability of robots in underground mining settings. More recently, the development of terrestrial/aerial hybrid platforms has resulted in more robust solutions that can lower the cost of transport compared to purely aerial vehicles, increase payload capacity, and resist collisions and physical interactions within potentially cluttered and narrow spaces. However, the complexity of integrating both modes of transportation into a single platform has resulted in only a few experimental prototypes being deployed and tested in underground mine environments.

Regarding aquatic platforms, several initiatives have demonstrated potential applications in flooded and partially flooded mine environments, primarily focusing on exploration tasks. These platforms are designed to navigate and gather data in challenging conditions where traditional land-based robots cannot operate. However, the increased complexity that water introduces to the design and

functionality of these robotic platforms has resulted in a relatively small number of viable solutions.

To address this challenge, some researchers and developers have introduced amphibious platforms that combine terrestrial and aquatic modes of operation. These hybrid platforms are particularly promising, as they offer greater adaptability to the dynamic and often unpredictable conditions found in mine settings with flooded galleries. By seamlessly transitioning between land and water, amphibious platforms can explore and perform tasks in environments that are otherwise inaccessible, enhancing the efficiency and scope of mining operations. Despite the promising nature of these solutions, the complexity involved in integrating both terrestrial and aquatic capabilities means that further research and development are required to refine these systems and expand their practical applications.

Future research in terrestrial, aerial, and aquatic robotic systems should aim to overcome the existing challenges in design complexity, energy efficiency, and adaptability. By focusing on the integration of hybrid locomotion methods, improving environmental awareness, and developing more robust platforms, these robots can be better equipped to handle the diverse and challenging environments they encounter. This will not only expand their applications, but also improve their effectiveness in sectors such as mining, construction, and exploration.

2.2 Mobile Modular Robotic Systems

A *modular robot* can be defined as a *"robot composed of parts that have independent functionalities but are able to interact with each other in one or more ways, resulting in an entity with new capabilities."* (Brunete et al., 2017). Typically, each module has distinct computational and actuation features, enabling smooth communication and coordination for complex task execution. These robots exemplify a novel design paradigm in robotics, distinguished by their ability to alter their structure and functions through the reorganization of their modules.

Unlike conventional robots, which are constrained by unchanging forms and functions, modular robots exhibit exceptional adaptability. These robots present numerous benefits compared to those with a fixed structure, primarily due to their flexibility and versatility. A key benefit of modular robots is their ability to tackle different tasks through the modification or addition of modules, which makes them ideal for environments that are constantly changing, such as search and rescue missions or exploration of unknown terrains (Kotay et al., 1998). Furthermore, modular robots offer the potential for improved efficiency and fault tolerance. Should a module cease to function or break down, the system is often capable of reconfiguring itself to work around the affected module, thus maintaining operational continuity (Murata et al., 2001; Tomita et al., 1999). Such self-repairing abilities significantly boost the system's dependability, an essential attribute for use in isolated or dangerous settings. Moreover, modular robots are economically advantageous under certain conditions. By integrating additional modules into an existing robotic framework, it is possible to reduce both development and manufacturing expenses, rather than creating entirely new machines for varied tasks (Yim et al., 2009). This modular strategy also supports system enhancements and adjustments, which can prolong both the utility and operational life of the robot.

Modular robots can be categorized based on several criteria, such as mechanical design, control systems, operational environments, and structural formation. Several research works (Ahmadzadeh

et al., 2015; Dokuyucu and Özmen, 2023; Liu et al., 2016; Moubarak and Ben-Tzvi, 2012; Vu et al., 2023) have documented notable progress in the domain of modular reconfigurable robotic systems following the aforementioned classifications.

Among the wide range of modular robots discussed in the literature, this dissertation specifically focuses on the progress made in modular mobile robots with reconfiguration abilities. According to Moubarak and Ben-Tzvi, 2012, this type of robot includes modules that function independently, interact with their environment, and link with other modules to change the overall configuration and enhance the functionality of individual modules.

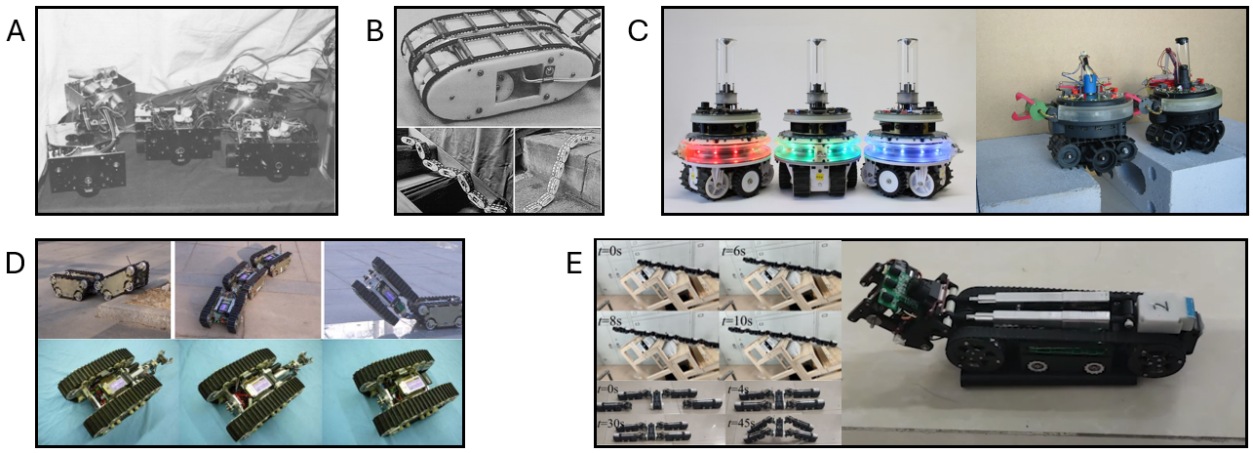


Figure 2.14: Examples of modular, self-reconfigurable mobile robotic systems. (**A**) CEBOT robotic system (Fukuda and Nakagawa, 1988). (**B**) Milibot train (Brown et al., 2002).(**C**) S-BOT robotic system (Mondada et al., 2004). (**D**) JL-I train configuration for three robotic modules (**top**) and JL-2 module featuring coupling mechanism based on a manipulator (**bottom**) (Guanghua et al., 2006; W. Wang et al., 2010). (**E**) Reconfigurable tracked robot system SMMRob (H. Li et al., 2022)

Each module in this category is equipped with sensors, computing units, and actuators, enabling independent movement and operation. These modules typically use standard locomotion methods such as wheels and tracks for effective movement. In addition, their design includes coupling mechanisms called docking interfaces, which allow multiple modules to connect and form a larger assembly. Mobile self-reconfigurable modular robots bridge the gap between self-reconfigurable robots and traditional mobile robotics. These solutions are known for their advanced swarm capabilities, and their reconfiguration features enable them to tackle complex tasks effectively (Dokuyucu and Özmen, 2023).

The development of dynamically reconfigurable mobile robotic systems began with the cell-structured robot (CEBOT), pioneered by Nagoya University. CEBOT consists of a collection of functional cells capable of communicating and maneuvering on flat surfaces, as well as connecting and detaching autonomously. Each cell has couplers at both the front and rear. The couplers' actuators are made of shape memory alloys (SMA), positioned on the outer couplers. Furthermore, each cell is equipped with casters that minimize ground friction, and their joints and wheels are powered by DC motors. All cells share the same dimensions, measuring 180 mm in length, 90 mm in width, and 50 mm in height, with weights ranging from 1.1 to 1.3 kg depending on the cell type. The bending joint cell has a movement range from -90 to 90 degrees. The mobile cell with wheels

includes a PSD (Position Sensitive Detector) sensor. Furthermore, should individual cells sustain damage, CEBOT is designed for automatic repair or replacement (Fukuda and Nakagawa, 1988).

Following CEBOT, another significant advancement to highlight is Milibot, developed in the early 2000s by Carnegie Mellon University. Milibot consists of a series of semi-autonomous, caterpillar-tracked mobile units, measuring 3 cm in height, 5 cm in width, and 10 cm in length, configured in a train-like formation to navigate substantial obstacles. These robots are equipped with a two-pin coupler and latch system, complemented by a corresponding receptacle on the opposite end, enabling the modules to connect and dock seamlessly. A robust torque actuator powers the coupling mechanism to position and secure the modules as required. The tracks cover most of the upper and lower surfaces and the areas between the tracks are smoothed to reduce drag and prevent snagging on terrain irregularities. The tracks also extend beyond the top and bottom surfaces, facilitating inverted operation. Each Milibot can reach speeds up to 20 cm/s on flat terrains, travel between 30 and 50 meters on a single battery charge, and generally fits within a 5-cm cubic space. Standard sensors include ultrasonic for detecting obstacles and measuring distances between modules up to one meter; infrared sensors for proximity obstacle detection (up to 10 cm); a tiny CMOS video camera (0.8-micrometer sensor) with a transmitter; and pyroelectric sensors for identifying humans and other heat-emitting entities.(Brown et al., 2002)

Among the most significant self-configurable mobile modular systems is the Swarm-bots (S-bot), which were developed between 2001 and 2005 at the Laboratory of Intelligent Systems at EPFL in Lausanne. Each s-bot, depicted in Figure 2.14 C, is a fully autonomous mobile robot with functionalities such as autonomous navigation, environmental perception, and object manipulation. In addition to these abilities, an s-bot can also communicate and physically connect with other s-bots in flexible ways, forming what is known as a swarm-bot. This collective robotic system is adept at handling tasks that challenge a single s-bot, including the exploration, navigation, and movement of large objects across uneven terrains (Dorigo et al., 2004). An individual s-bot weighs approximately 700 gr and stands 19 cm tall. Furthermore, if its two manipulation arms and the transparent pillar on top are removed, the s-bot can fit inside a cylinder with a diameter and height of 12 cm (Gross et al., 2006). The mobility of the system is facilitated by a combination of two tracks and two wheels, where each track is connected to the corresponding wheel and operated by a separate motor. The same motor drives both the wheel and the track on one side, creating a differential drive system controlled by two motors, referred to as Differential Treels Drive (Mondada et al., 2004). Each s-bot is equipped with essential navigation sensors, including infrared proximity sensors, light and humidity sensors, accelerometers, and incremental encoders for each degree of freedom. Additionally, each robot possesses sensors and communication tools for detecting and interacting with other s-bots, such as an omnidirectional camera, color LEDs around the robot, local color detectors, and sound emitters and receivers. Alongside numerous environmental detection sensors, several sensors provide each s-bot with data regarding physical interactions, forces, and responses at the connecting joints with other s-bots. These sensors include torque sensors in most joints and traction sensors in the connecting belt. Reconfiguration is accomplished through a robotic gripper or a manipulator arm integrated into the robot's structure, enabling both rigid and semi-flexible connections. The rigid gripper facilitates the lifting of another module, whereas the arm allows flexible connections that allow the modules to maintain relative movement freedom with each other (Dorigo et al., 2006).

Another significant example is the JL-I, followed by its updated counterpart, the JL-2 platform. This robotic system, depicted in Figure 2.14D, consists of multiple identical, self-sufficient modules, each equipped with two powered tracks, a docking mechanism, and mechanisms for pose adjustment that include both a serial and a parallel mechanism. These mechanisms jointly create a 3-DOF active spherical joint between every pair of adjacent modules (Guanghua et al., 2006). The docking mechanism transitioned from a pin and hole design in the JL-I to a manipulator-based design in the JL-2, enabling the modules to connect and form a train-like structure suitable for uneven terrains or to detach for individual operations (W. Wang et al., 2010). The active spherical joint permits rotation around the X-axis, Y-axis, and Z-axis. Repeating these fundamental processes allows for various three-dimensional configurations, leading to multiple practical functionalities.

More recently, SMMRob was presented as a self-contained and reconfigurable modular robotic system capable of docking in various configurations, including chain formations. The SMMRob motion module (Figure 2.14 E right) features a slim rectangular chassis with tracks, a docking mechanism that uses a parallel gripper and a 2-SPS parallel joint actuation system, along with electronic hardware for sensing, control, communication, and localization. Each robot module measures 296 mm in length, 68 mm in height and 60 mm in width, with a weight of 900 gr. The docking mechanism is mounted on the front of the structure, with its corresponding passive interface located at the rear of the robot. The robot is capable of forming tree-like assemblies (Figure 2.14 E left) due to its joint actuation system. Furthermore, SMMRob includes not just motion modules but also modules for sensing, power, and base functionalities. The uniform SMMRob modules, each carrying different payloads, can move, sense, manipulate, and dock autonomously. In a tree-like configuration, the motion modules can construct the body, while the sensing modules can serve as the head of the robotic system (H. Li et al., 2022).

2.2.1 Self-assembly mechanisms for modular reconfigurable robots

Coupling mechanisms are crucial for the functionality and versatility of reconfigurable modular robots. They enable modules to interlock, communicate, and collaborate seamlessly, facilitating the assembly of complex structures tailored to specific tasks and environments. These mechanisms can be categorized into two primary types: intra-robot coupling and inter-robot coupling (Saab et al., 2019).

Intra-robot coupling occurs between modules within a connected group, allowing fluid movement in lattice-based structures or dynamically changing chain-based structures (Dokuyucu and Özmen, 2023). This type of coupling enables modules to reconfigure themselves into different shapes during operation, enhancing the robot's adaptability to the environment and resilience in various scenarios.

In contrast, inter-robot coupling involves separate and unconnected groups of modules coming together to execute synchronized tasks before disassembling back into individual modules. This coupling mechanisms can be further differentiated based on the method used for the coupling maneuver, which can be either close-contact or manipulator-based. The primary distinction between these methods is the minimum distance required between modules to execute the docking maneuver.

Coupling mechanisms can also be categorized by the type of force used to connect modules (Saab et al., 2019). These include:

1. **mechanical connectors**, such as pin-and-hole, hooks, lock-and-key, and shape matching.
2. **magnetic connectors**, which can be either passive or based on electromagnets.
3. **adhesive and vacuum connectors**, which are less common solutions, are usually employed in modular soft robots (Zhang et al., 2020).

Given that this dissertation focuses on mobile reconfigurable modular solutions, only inter-robot coupling mechanisms are presented. Focusing on the above-mentioned solutions (Section 2.2), there is a clear transition from close-contact approaches in early developments (CEBOT, Milibot, JL-I) to manipulator-based approaches in more recent solutions (S-bots, JL-2, SMMRob). The increased tolerance to misalignment and the ability to form more complex structures to adapt to the environment compensate for the increased complexity in the design and control of these platforms. In the following, the solutions implemented for manipulator-based coupling mechanisms are described in detail.

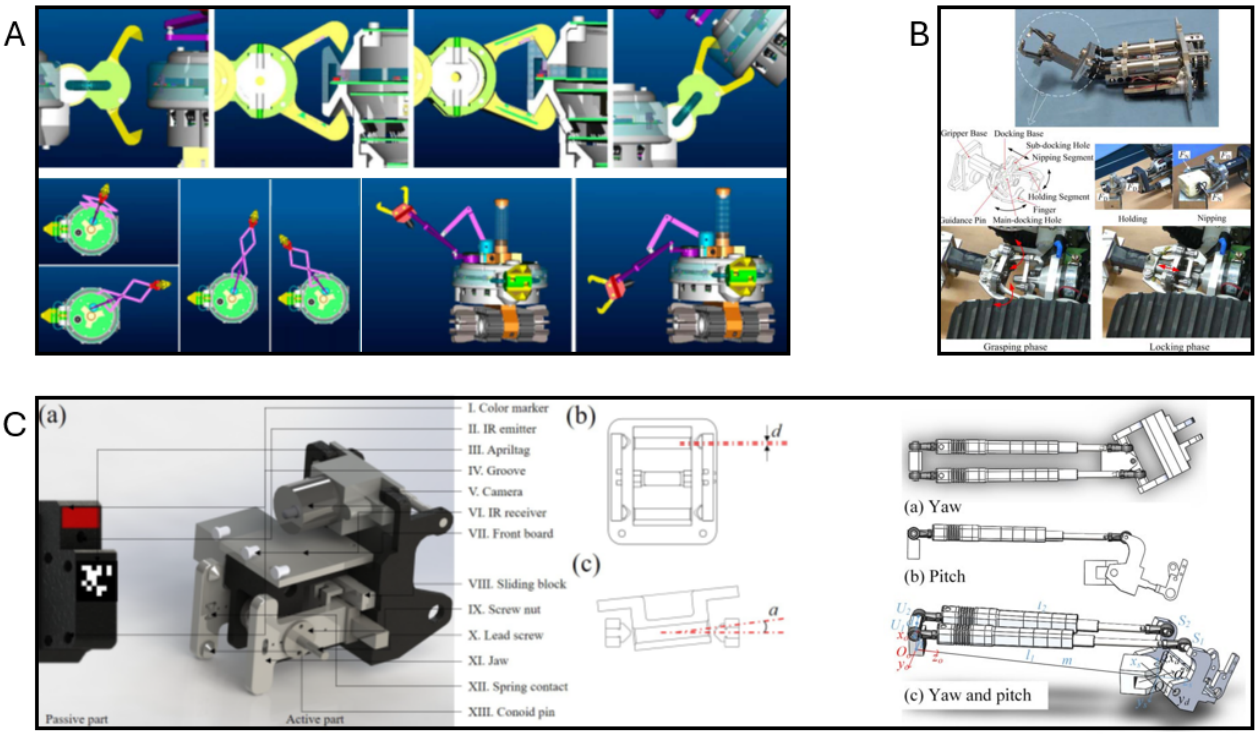


Figure 2.15: Examples of manipulator-based coupling mechanism for modular self-reconfigurable robots. (**A**) S-Bot rigid gripper (**top**) and flexible gripper (**bottom**)(Mondada et al., 2004). (**B**) JL-2 manipulator with spherical joint mechanism (W. Wang et al., 2010).(**C**) SMMRob docking mechanism (**left**) and joint actuation mechanism (**right**) (H. Li et al., 2022).

S-bots can form a swarm-bot configuration through two types of physical interconnection: rigid and semi-flexible. Rigid connections between s-bots are achieved using a rigid gripper mounted on a horizontal active axis (Figure 2.15 A top). This gripper has a large acceptance area, enabling it to securely grasp at any angle and, if needed, to lift another s-bot. The large acceptance area is crucial for connections among independent autonomous robots on uneven terrains. Semi-flexible connections (Figure 2.15 bottom) are facilitated by a gripper at the end of a flexible arm, designed

based on the DELTA robot, and actuated by three servo-motors located at the attachment point on the main body. The three degrees of freedom allow the arm to extend and move laterally and vertically. The gripper at the arm's end, termed as the "flexible gripper" by the authors, is similar to the rigid gripper. Its orientation is maintained in a default position by the flexibility of the cables but can rotate around a vertical axis (Mondada et al., 2004).

For JL-2, the coupling manipulator comprises a two-DOF parallel mechanism and an end gripper, as shown in Figure 2.15. The parallel mechanism includes two parallel ball screws, the gripper base, and the supporting pole attached to the robot platform. The gripper mounted on the gripper base consists of a screw-nut mechanism and two fingers that can rotate around two shafts, respectively. Two pins are fixed with the nut (Docking base) and pass through the grooves of the fingers known as cam grooves. When the docking screw turns, the pins will move forward or backward, causing the gripper to close or open due to the special shape of the cam groove. To position the mass center of the docking manipulator close to the robot's center, all driving motors are mounted on the opposite side of the gripper. A mechanism with two synchronous belts, two pairs of gears, and a slide key mechanism is used to transfer the output torques of the motors to the two parallel screws and the docking screw, respectively. The docking manipulator's functions are: 1) grasping and manipulating objects; 2) holding the docking disk of the rotation unit on the other robot; 3) adjusting the pitching and yawing postures between two connected robots (W. Wang et al., 2010).

For SMMRob, the coupling mechanism is composed of two distinct parts: an active component at the front of one robot module and a passive component at the rear of another robot module. In the center of the passive component, there is a rectangular solid with two conoid grooves on each side, and the active component features two corresponding conoid pins on each side. During docking, the conoid pins are inserted into the grooves. Even if the pins and grooves are not perfectly aligned, within a certain range of displacement distance and orientation, the conoid shape can guide the two parts to fully align. The passive system operates without power. The active component can drive two opposing jaws in parallel, allowing the pin to be inserted into or withdrawn from the grooves. The jaw opening and closing are controlled by a pair of bidirectional lead screws and nuts. Additionally, the upper and lower sliding blocks on the active component's frame can support the docking mechanism for heavy loads. The lead screw is powered by a DC motor through gear transmission. A linear potentiometer mounted on the frame measures the nut's displacement, providing feedback for the jaws' opening and closing. After docking, the spring contact of the active component can touch the contact socket of the passive component to enable CAN bus communication. The lead screw and nuts are self-locking, ensuring that the docking mechanism remains securely connected and does not unexpectedly separate when the lead screw is stationary with the motor power off (H. Li et al., 2022).

While the provided solutions have shown their utility in various applications, they may not be ideal for underground mining scenarios. In such environments, modular reconfigurable robots encounter significant obstacles due to uneven and rugged terrain, limited visibility, and the presence of dust and debris. The intricate design and control of manipulator-based systems can intensify these challenges, making precise alignment and reliable operation more difficult. Additionally, the bulkiness and rigidity of conventional coupling mechanisms can impede maneuverability and adaptability in confined and irregular spaces. The use of soft continuum robotic arms offers a promising solution to these issues. Their inherent flexibility and adaptability enable them to better navigate and operate

in complex and unpredictable environments. Soft robotic arms can absorb and adapt to impacts, minimizing the risk of damage from collisions with rough terrain. Their versatility enhances the robot's capability to perform a broader range of tasks, from delicate manipulations to robust handling, making them a crucial innovation for enhancing the safety, efficiency, and effectiveness of modular robots in underground mining operations. Although the design and control complexities of soft robotic systems remain a significant challenge, the potential benefits in terms of adaptability, safety, and versatility make this an important area for future research and development.

2.3 Alternative sensing technologies for unstructured underground environments

Operating and maneuvering in unstructured subterranean settings presents considerable difficulties for field robots, as they contend with harsh conditions like insufficient or absent lighting, environments where the Global Positioning System (GPS) is unavailable, high levels of dust, and rapidly changing circumstances. Recognizing that the majority of advanced perception systems for subterranean exploration, which primarily depend on cameras and LiDAR, can rapidly deteriorate under such harsh conditions, it is crucial to consider alternative innovative solutions (Ebadi et al., 2024).

An innovative method involves employing touch-based sensors to replace or enhance the perception system of mobile robots (Pearson et al., 2011). This approach leverages the sense of touch to provide more reliable data in environments where traditional vision-based systems might struggle due to lighting conditions, transparency, or occlusions. Among various touch-based sensors, biomimetic whisker sensors have emerged as a promising alternative due to their proven robustness, simplicity, versatility, and accuracy in various applications, such as object localization (Lin et al., 2022; Pearson and Salman, 2019; C. Zhao et al., 2022), as well as contour and texture recognition (Solomon and Hartmann, 2010).

Biomimetic whisker sensors, inspired by the tactile sensing capabilities of mammal whiskers, have demonstrated exceptional potential to improve robotic perception. These sensors mimic the way animals use their vibrissae to detect and interpret physical interactions with their surroundings, allowing robots to gather detailed information about nearby objects and surfaces (Prescott et al., 2009). This capability is especially beneficial for tasks that require precise detection and manipulation of objects in cluttered or complex environments, such as in search and rescue operations or in underground exploration and surveying where robots must navigate and interact with highly irregular environments.

Putting emphasis on robotic applications, integrating active and passive whiskers into mobile robots such as Whiskerbot (Figure 2.16 A), Shrewbot (Figure 2.16 B), SCRATCHbot (Figure 2.16 C), and robotic manipulators, as depicted in Figures 2.16 D and 2.16 E, has demonstrated considerable potential for tasks such as obstacle avoidance, object recognition, and simultaneous localization and mapping (SLAM) (Pearson et al., 2007, 2010, 2013; Salman and Pearson, 2016a, 2018). Active whiskers, capable of movement and environmental adaptation, provide dynamic feedback, improving the robot's ability to traverse unknown or unstructured terrains. In contrast, passive whiskers deliver constant sensory input, aiding in a stable and continuous perception of the robot's immediate environment.

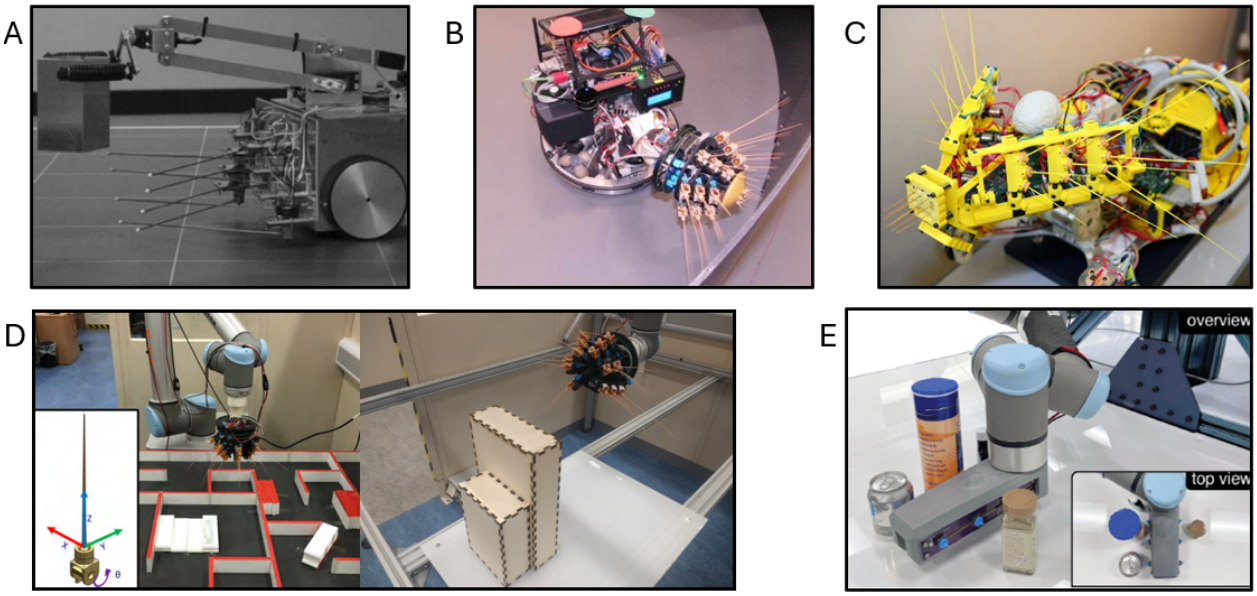


Figure 2.16: Examples of whisker sensor implementations in robotics. Top row: Implementations in mobile robots. (**A**) Whiskerbot (Pearson et al., 2007). (**B**) Shrewbot (Pearson et al., 2013). (**C**) SCRATCHbot (Pearson et al., 2010). (**D**) Whisker-RatSLAM Applied to navigation (**left**) and 6D Object Identification (**right**) (Salman and Pearson, 2016a, 2018). (**E**) Contact Localization on UR robot manipulator (Lin et al., 2022)

Nevertheless, there has been limited effort directed towards environment reconstruction tasks. Mapping 3D spaces introduces additional challenges, as whisker-based sensors must effectively navigate and interpret spatial information. Accurate 3D mapping requires not only detecting surfaces but also understanding their spatial relationships, which is more complex with tactile sensors than with traditional vision systems. Factors such as environmental variability, surface textures, and the need for real-time adaptability add to the complexities of developing robust models for whisker-based sensors in 3D-mapping applications. Environmental variability refers to the different types of surfaces and materials that a robot might encounter, each with its own texture, hardness, and other physical properties that can affect sensor readings. Real-time adaptability is crucial as the robot must continuously process sensory information and adjust its movements accordingly, which demands high computational efficiency and sophisticated algorithms. Developing robust models for whisker-based sensors in these scenarios involves extensive testing and refinement to ensure accuracy and reliability under diverse conditions.

Chapter 3

Research Methodology

"He who seeks for methods without having a definite problem in mind seeks in the most part in vain."

– David Hilbert

This chapter presents the mechatronic system design methodology employed in the development of the RM2 robot system for mining operations, a central focus of this doctoral thesis as outlined in Chapter 1. The complexity of creating a modular robotic system for mining operations requires a structured approach to design and development.

The mechatronic design process for the RM2 encompasses multiple interconnected elements: basic mechanical structures, actuators with power transmission mechanisms, feedback sensors, control electronics, and specialized control and communication software. This process begins with the conceptualization of the overall robot system before progressing to the design of individual modular components. The interdisciplinary nature of the project, combined with the multitude of components involved, including numerous actuators, sensors, and electronic elements, requires a methodical and goal-oriented strategy. To ensure timely progress and effective outcomes in this complex challenge, it is crucial to adhere to systematic methodologies that prioritize the design process and organize the development phases of the modular robot.

In this chapter, a contextualization of the project in which this thesis was developed is presented, as well as a description of the design methodology used throughout the research process, and the metrics used to evaluate the maturity of the solutions presented.

3.1 ROBOMINERS mining concept

As mentioned in Section 1.1, the ROBOMINERS exploitation concept envisions a novel environment, where modular mining machines are transported to the mine site through a large diameter borehole, subsequently self-assembling and commencing operation, as illustrated in Figure 3.1. In this scenario, mines are designed as an artificial "ecosystem" without human life support or the creation of extensive underground infrastructure. The mining operation might last only a year or less. Once the operation is completed, the modular miner is disassembled and extracted through the borehole to be utilized at another site. (Lopes et al., 2020).

To achieve this goal, the project segmented the research and development efforts for the future robotic miner into seven key areas: biological inspiration; underground localisation; behavior, navigation and control; mechatronics and actuation; modularity; autonomy and resilience; and selective mining. Within the project's scope, three unique technology demonstrators (RM1, RM2, RM3) were developed to address various of these areas. The robotic prototypes, shown in Figure 3.2, aim to investigate different robotic aspects to meet the project's long-term objective of fully autonomous robotic mining systems. In this approach, each platform is intended to examine a specific set of the mentioned areas. A summary of the technical specifications for each platform is provided in Table 3.1.

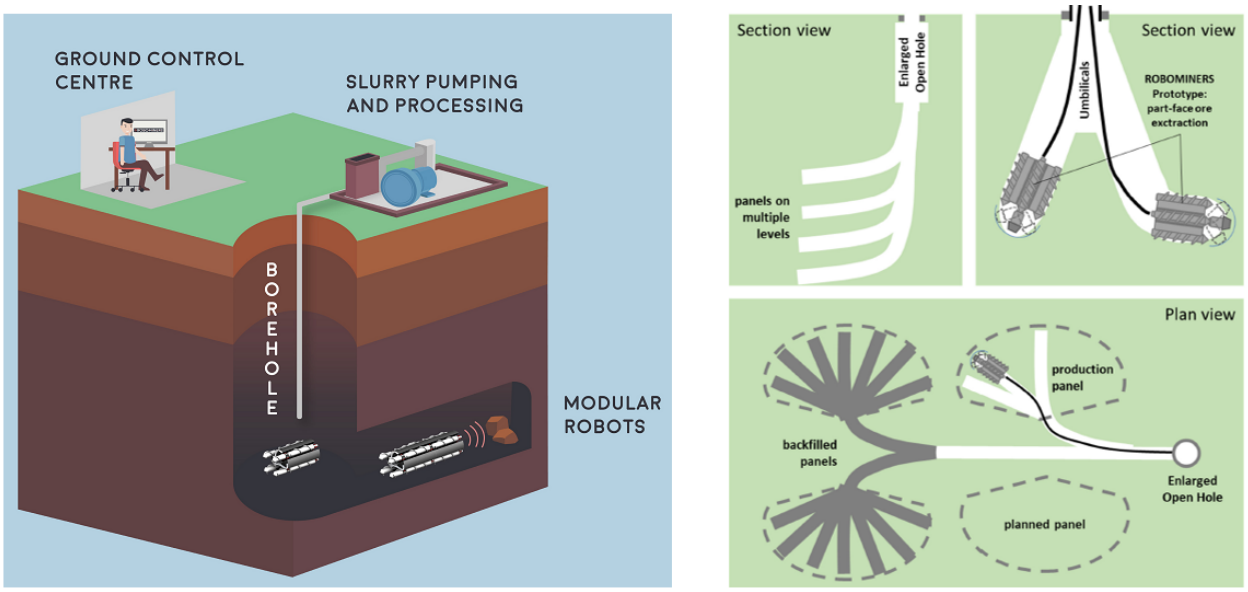


Figure 3.1: ROBOMINERS concept. (**Left**) Deployment of modular prototypes through a borehole to later self-assemble and perform underground mining operations (Stein and Correia, 2023). (**Right**) Bioinspired mining layout using a part-face cutter head on a tethered robotic miner in a keyhole mining operation (Pinkse et al., 2022).

The RM1 robotic system serves as a full-scale demonstrator for real-world operational settings. It comprises three robotic modules: two mobile platforms and a production tool unit, all interconnected by powered articulated joints. The first and second mobile platforms together feature six screw traction units—four on the first and two on the second—which facilitate the robot's movement and provide support against tunnel walls during excavation. Each screw traction unit is linked to its module via two independently controlled hydraulic struts, allowing the robot's diameter to be adjusted to match the tunnel's diameter by changing the screw position with respect to the tunnel wall, thereby increasing the contact force. In addition, screw traction units can be longitudinally adjusted using a hydraulic cylinder, enhancing their adaptability to tunnel walls. These features enable potential peristaltic earthworm-like movement. The mobile modules are joined by an active articulated joint with two active degrees of freedom and one passive degree (x, y, rotation around z). This joint helps steer the robot and allows for adjustments in weight distribution in the traction units. Although the modules are structurally differnt, modularity is maintained in the subsystems and structural components. The production tool module is attached to Module 1 via a three-degree-of-freedom joint (x, y, z), which allows manipulation of the cutting head at the end of the production

tool module (Hakonen et al., 2023).

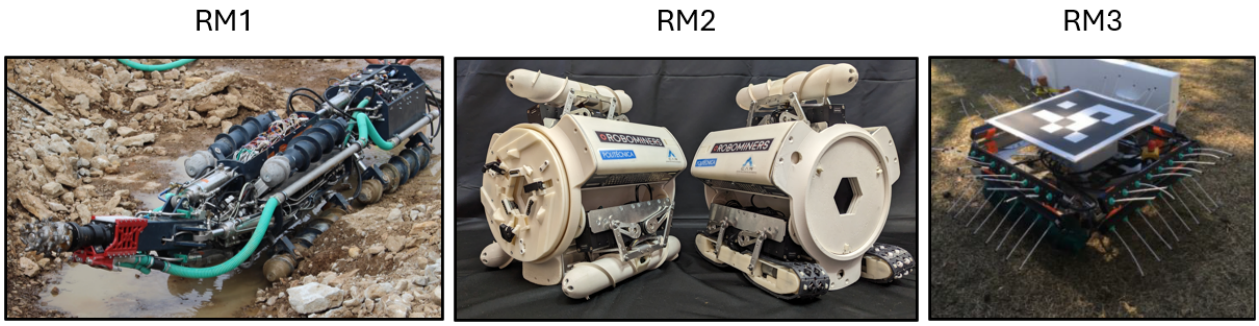


Figure 3.2: ROBOMINERS prototypes. (**Left**) RM1 full-scale robotic miner (Hakonen et al., 2023). (**Center**) RM2 scaled model. (**Right**) RM3 lab prototype (Piho et al., 2023).

Table 3.1: ROBOMINER prototypes technical specs.

Technical Specs	RM1	RM2	RM3
Drive system	Hydraulic	Electric	Electric
Power	200-2500 W per Module	48-180 W per module	150-300 W
Sensors	48 IMU Reflectance spectrometers LIBS Current and Voltage 30x water pressure Temperature Production tool arm Leg joint angles	Motor Current Battery Status IMU 9-DoF Magnetic Encoders Dynamixel sensors Whisker sensors	Motor Current 48 IMU, 6-DoF IMU Reflectance spectrometers Temperature Water level 2x RGBD Camera 2D LiDAR Whisker sensor
Mass	1350 kg (Three modules)	4 kg (Single module)	50 kg
Dimensions	5,000 mm (Three modules) Diameter (800mm-1000 mm)	220 mm (Single module) Diameter (300-400 mm)	1125 x 1045 (width x lenght) mm
Main Function	Navigation, Mining (Full-scale robotic miner)	Modularity, self-assembly and reconfigurability (lab-scale)	Localization and environmental sensing (lab-scale)

The RM3 is a lightweight platform intended for testing locomotion and sensors, focusing on investigating various localization and environmental sensing methods in field conditions at a low Technology Readiness Level (TRL) through the creation of sensor fusion, mapping, localization, and navigation algorithms. This prototype mimics the full-scale prototype (RM1) using Archimedean screw locomotion. The sensor suite of the prototype includes a SICK S300 2D LIDAR and two Intel RealSense D455 depth cameras, one for external tracking of the robot's pose with ArUco markers and another for visual SLAM. These two techniques are utilized to establish a reference for the robot's pose to assess the developed perception methods. In addition, a custom-made array of whisker sensors was created to carry out tactile SLAM tasks. To provide more flexibility in whisker positioning, several whisker modules were produced, each comprising 8 whisker sensors with a custom electronic board and a waterproof connector. The perception system is further enhanced with two spectrometers mounted at the front of the robot. The spectrometer modules consist of the

measurement unit housed in a 3D printed waterproof casing with a window facing the ground (Piho et al., 2023).

Lastly, the RM2 robotic system, the focus on this dissertation, is a conceptual scaled version of the robotic miner (RM1) and focuses on exploring modularity, self-assembly, and reconfiguration capabilities to perform more complex tasks and ensure resilience. For seamless integration of all the modules comprising the RM2 robot, a systematic design methodology is employed.

3.2 Methodology Process

The research methodology used in the development of this thesis is based on the Association of German Engineers (VDI) 2206 guideline entitled "Design Methodology for Mechatronic Systems" (Gausemeier and Moehringer, 2002). The guideline provides a structured approach for the development and design of complex technical systems, especially those that include mechanical, electrical, and software components, which are typical of mechatronic systems. The VDI guideline provides recommendations and procedures for system modeling, requirements analysis, design processes, and component integration to ensure efficient and effective development processes. To apply the VDI 2206 methodology to the design of a modular robot, a structured approach should be followed, as presented by the authors, that includes seven key phases:

1. *Requirements*: A comprehensive analysis of the intended application provides a clear understanding of the tasks and functionalities required of the modular robotic system. These requirements are refined and formalized to establish the necessary design specifications. In the context of this modular robotic system, which is intended to be versatile and adaptable, the requirements include aspects such as modular architecture, self-assembly mechanisms, and adaptability to unstructured terrains. After analyzing the motivation and framework of the project presented in Section 1.1, the following list of requirements can be derived.

   R.1 The robotic system must consist of modular robots that can be easily assembled to form larger structures.

   R.2 The robotic system must be capable of traversing irregular terrains under different conditions.

   R.3 The robotic system must optimize its footprint to be able to be sent to a hypothetical mine through a borehole.

   R.4 The robotic system must have an adaptable coupling mechanism to assemble different modules in unstructured environments. The mechanism must account for misaligments between modules caused by irregular terrain.

   R.5 The robotic system must be able to share energy between the different robotic modules to increase the resilience and fault tolerance of the system.

   R.6 The robotic system must be able to reconfigure during operation.

   R.7 The robotic system must be able to perform mine-related tasks (exploring, mapping, mining) in a scaled-down version.

2. *System design*: Based on the defined requirements, the design methodology proceeds to conceptualize a solution that spans multiple domains and captures the fundamental physical and logical attributes of the envisioned platform. This involves decomposing system functions into manageable subfunctions, each addressing key aspects such as modularity, self-assembly, and terrain traversal. Iterative refinement is performed to identify appropriate operating principles and solution elements for each subfunction, ensuring alignment with the overall design goals.

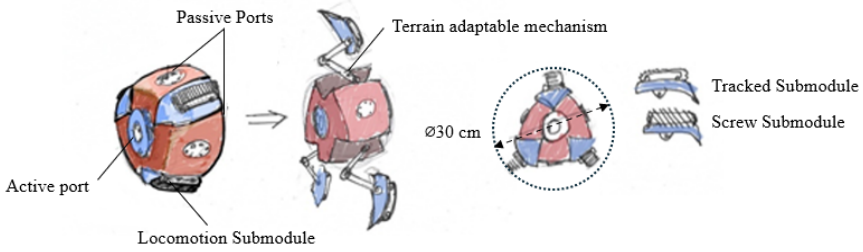


Figure 3.3: Robotic modular system conceptual drawing specifying the main components of the system, including the active and passive ports, terrain-adaptable mechanism, modular design and compact design

Concerning the presented robotic system, a first sketch of the modular solution (Figure 3.3) was developed taking into consideration the set of requirements defined in the previous step.

3. *Domain specific design*: With the high-level solution concept established, detailed design work is performed within each domain (mechanical, electrical, and software) to refine the specific aspects of the system. Domain-specific considerations, including rigorous calculations and design iterations, are essential to ensure functional performance, especially for critical functionalities such as modularity, self-assembly and adaptability to varying terrain.

4. *System integration*: The output of domain-specific design efforts is seamlessly integrated into a cohesive system, facilitating the analysis of interdependencies and interactions between different components and subsystems. This integration phase ensures that the modular robotic system functions in harmony as a unified entity, effectively exploiting its diverse capabilities to achieve the overall objective presented in Section 1.2.

5. *Verification/Validation*: Continuous assessment of design progress is performed to verify compliance with specified solution concepts and requirements. Rigorous validation procedures corroborate that actual system characteristics match the desired results, validate the effectiveness of the design approach, and ensure that the modular robotic system meets its intended performance criteria.

6. *Modelling and model analysis*: Throughout the design phases, an emphasis is placed on modeling and analyzing system characteristics using advanced computational tools and simulation techniques. This iterative process helps refine the design, identify potential performance bottlenecks, and optimize the behavior of the system, thus improving the overall effectiveness and efficiency of the modular robotic system.

7. *Product/Unit*: The product, in this case the robotic system, is the result of a successfully

completed macro cycle, as shown in Figure 3.4. It does not exclusively represent the finished prototype, but the ongoing development of the future product (product maturity). As an example, Figure 3.5 exemplifies the iterative process and continuous evolution of the robotic solution. The maturity levels can be reflected at different stages of prototype development. An alternative to measuring the level of maturity of a solution can be done using the Technology Readiness Level (TRL) scale.

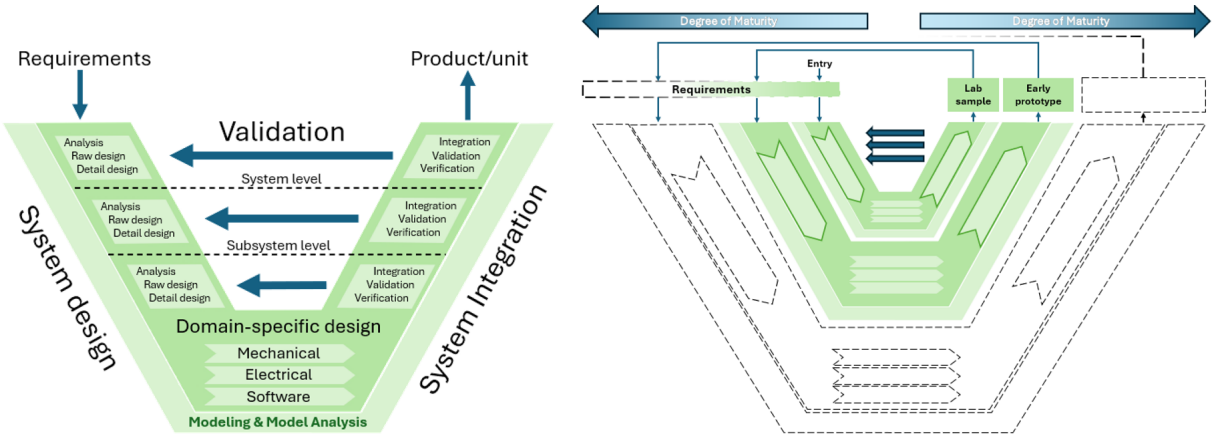


Figure 3.4: General workflow in the development of mechatronic systems according to VDI 2206 guideline (Gausemeier and Moehringer, 2002).

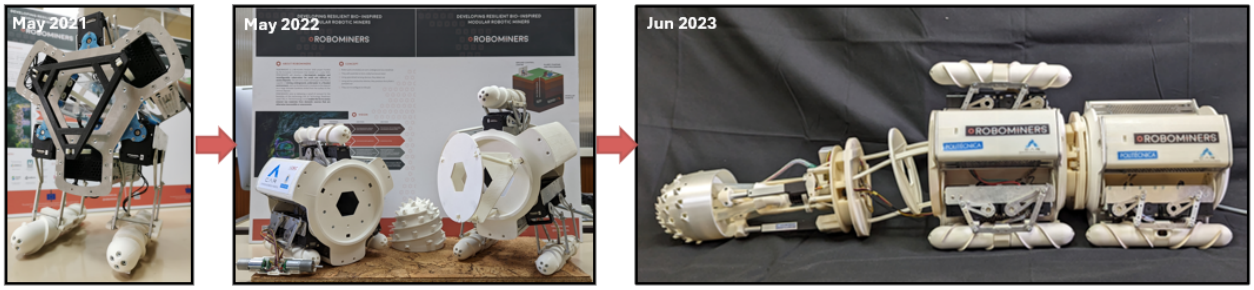


Figure 3.5: Integration of subsystems over time to the modular robotic system RM2.

3.3 Technology Readiness Levels

According to the methodology used in the development of the thesis, the Technology Readiness Level (TRL) measurement scale was used to assess the overall progress of both the system and its components. Initially introduced by NASA in the 1970s (Sadin et al., 1989), the TRL serves as a tool for gauging the maturity of emerging technologies on a scale ranging from 1 to 9. Although originally designed for space programs, it has since been extended to evaluate the maturity levels of various technologies. The TRL scale received further formalization in 2013 through the ISO 16290:2013 standard (International Organization for Standardization, 2013). Subsequently, the European Commission adopted this scale in 2014 for the EU Horizon 2020 program (Héder, 2017).

TRLs serve as a tool to monitor and refine the progress of a large-scale system integration, thus facilitating better execution in terms of validity, reliability, project performance, and time management. This metric can be used to track the evolution of a system or subsystem from a theoretical concept to a commercially finished product. The process of going from TRL-1 to TRL-9, presented in table 3.2, typically involves years of academic study, prototype development, component construction and testing, integration of tested components into other systems, and additional laboratory and field testing. A common approach to maturity levels is to divide them into three main stages: research, development, and deployment.

Table 3.2: Technology Readiness Level definitions and descriptions. Source: Hirshorn and Jefferies, 2016

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical or experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions and definition of relevant environment.
5	Component and/or breadboard validation in a relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions and definition of scaling requirements.
6	System/sub-system model or prototype demonstration in a relevant environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform.	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system "flight proven" through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

In the initial research phase (TRLs 1 to 3), a basic idea is refined into a more concrete concept.

The concept is then tested in a controlled environment to determine its technical feasibility. As TRLs 4 to 6 progress, the focus shifts from research to system design, testing, and integration. This transition can be challenging as the solution moves from laboratory experiments to real-world scenarios, typically occurring between TRLs 4 and 5. Often referred to as the *valley of death*, as described by Gbadegeshin et al., 2022, this phase represents the gap between academic ideas and practical industrial products. Lastly, when TRL 7 is achieved, the focus of the remaining levels is shifted toward deployment, since the system has essentially reached its final form.

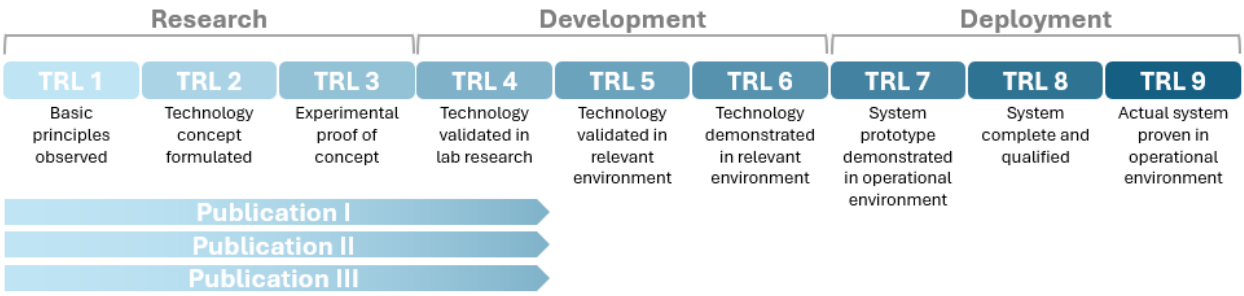


Figure 3.6: Technology Readiness Levels (TRL) diagram to represent the level of maturity of the solutions presented by this thesis.

Figure 3.6 provides an overview of the Technology Readiness Level (TRL) scale and the maturity level achieved by the solutions presented in each publication within this thesis. The research conducted in this dissertation focuses on the design and development of innovative solutions for underground mining robots. The main objective is to investigate the feasibility of implementing robotic concepts such as modularity and self-assembly in mining robots in a controlled laboratory environment. Publications from PI to P.III reach TRL 4, where the design and basic operating principles of the prototypes are validated in controlled laboratory conditions.

Chapter 4

Results and Discussion

"Above all, don't fear difficult moments. The best comes from them"

– Rita Levi-Montalcini

This chapter presents a detailed examination of the solutions presented in publications **P.I** through **P.III**, with a particular emphasis on fulfilling the research objectives outlined in section 1.2. The primary contributions (**C.1-C.6**) are summarized in Section 1.3. In this chapter, a summary and discussion of the experimental results are also provided. Before diving in, if it is in the reader's interest to explore more about the work, then please refer to the Publications section for further details. To facilitate the understanding of the interrelationship and interdependence of the publications that make up this thesis, Figure 4.1 provides a visual summary.

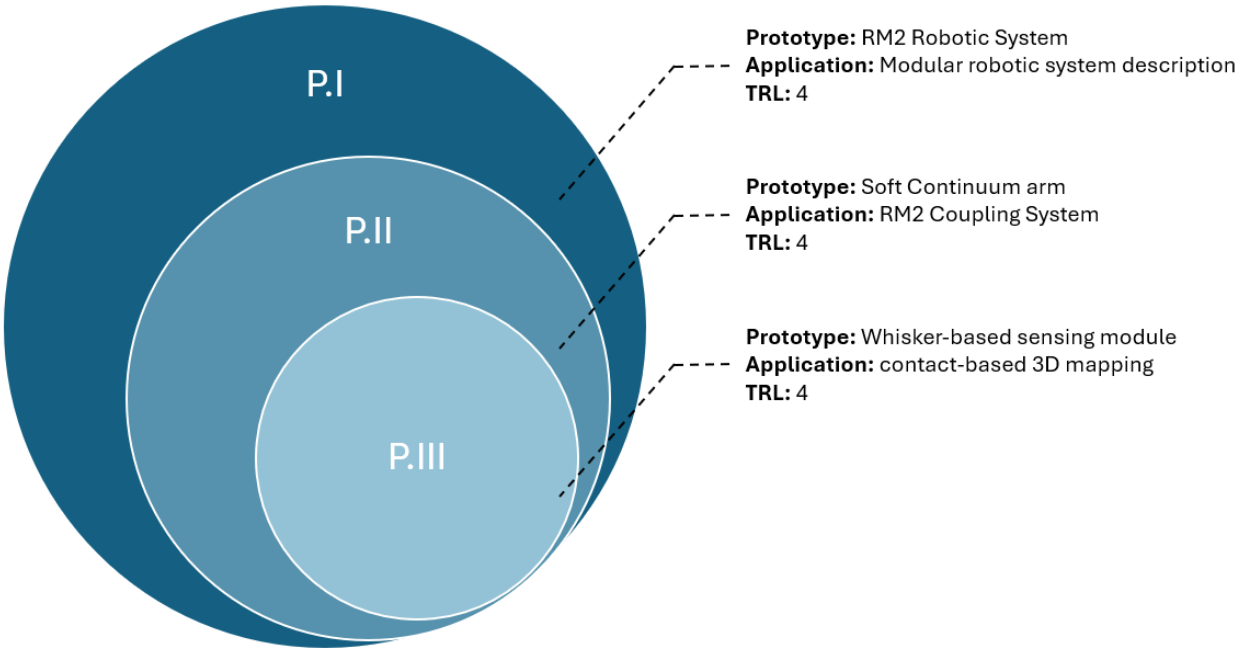


Figure 4.1: Publications diagram used for this thesis by compendium, highlighting the interrelation and differences.

The publications **P.I - P.III** follow a structure that progresses from general to specific. In this context, **P.I** outlines the robotic system, with a focus on the mobile platform and the different locomotion submodules, and demonstrates the overall functionality of the system. Next, **P.II** describes the conceptualization, design, and construction of an innovative soft continuum arm, which serves as the coupling mechanism for RM2 robotic modules. This includes a detailed description of the working principle, hardware, a study of material selection, modeling of the arm, experimental validation of the proposed model, and a demonstration of the mechanism's functionality. Finally, **P.III** details the design and development of a sensing module capable of mapping unstructured 3D environments, with a particular focus on mines, using whisker-based sensors. The study includes hardware description, sensor modeling, and experimental validation and verification on different robotic platforms to evaluate the prototype's performance. This is further elaborated in the appendices, where the proposed solution is integrated into the robotic module.

The remainder of the chapter is divided as follows. First, Section 4.1 presents the proposed robotic system with a detailed description of the mobile robot RM2. Next, Section 4.2 focuses on the soft robotic coupling mechanism for the RM2 module. Lastly, 4.3 presents a sensing module for environment reconstruction that can be integrated into different robotic manipulators, including the soft robotic arm that serves as the coupling mechanism for the RM2 module.

4.1 Modular Robotic System Description (Publication P.I)

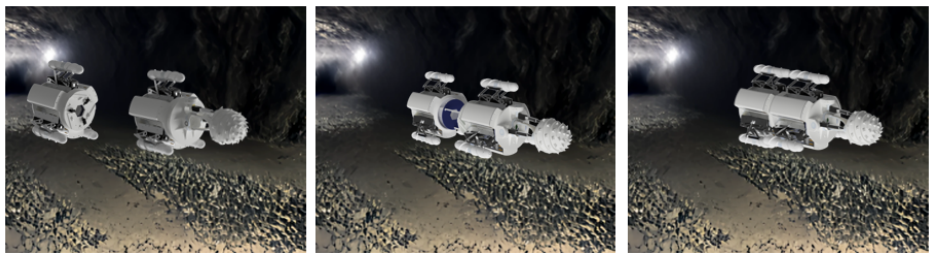
The publication **P.I** introduces a study on the design and development of a modular robotic system for mining environments (**O.1**). This system features the RM2 robotic module, designed as a proof-of-concept to explore the principles of adaptability, modularity, and self-configuration in the context of underground mining operations (**O.1.1**). The article includes an overview of the modular robot system, providing detailed descriptions of its various modules, locomotion mechanisms, and robotic submodules. Consequently, it presents the kinematic model of the robot, offering insights into the derivation of its closed-chain, parallel mechanism for efficient locomotion and terrain adaptability (**O.1.2**). Finally, the article includes a series of tests that demonstrate the flexibility of the system through different configurations, along with initial evaluations that validate the designs of the locomotion subsystems in a controlled laboratory environment (**O.4**).

4.1.1 Introduction

The deployment of modular robotic systems is presented as a promising approach to address the challenges that will impact future mining operations (Sayed et al., 2022). These systems consist of individual robot modules that can be interconnected to form a larger and more capable robotic system, providing inherent flexibility and versatility. This adaptability allows robots to adapt seamlessly to changing conditions, perform complex tasks, and achieve various goals, as presented in Figure 4.2.

Developing technology demonstrators is crucial in the innovation process, as they allow testing, optimizing, and validating concepts and designs on a small scale before moving on to larger platforms. This strategic approach saves valuable time and resources. Technology demonstrators serve as a proving ground where engineers and designers can assess the feasibility and functionality of their ideas in a controlled environment. Conducting tests and optimizations on a smaller scale can

help identify and address potential flaws and inefficiencies early in the development process. This iterative refinement improves the overall performance and reliability of the technology. Additionally, technology demonstrators provide a cost-effective means of validation. To evaluate the viability of their concepts, researchers can use smaller-scale prototypes instead of investing significant resources in full-scale implementations. This approach ensures that only the most promising and effective ideas progress to the larger, resource-intensive stages of development.



a. b. c.

Figure 4.2: Modular robotic conceptual solution that allows collaboration between robotic modules to perform more complex tasks in mining environments. (**a**) Different robotic modules are deployed in a mine. (**b**) The robotic module that features the cutting head ask the other robotic module to assemble to perform a mining task and a coupling maneuver is performed to form a larger robotic structure. (**c**) The resulting structure, made up of two mobile platforms and a cutting module, is assembled to perform mining tasks.

Small-scale testing and optimization also accelerate the innovation timeline. Early identification and resolution of issues contribute to a more efficient development process when scaling to larger platforms. This minimizes the risk of costly mistakes and allows for a smoother transition to full-scale implementation. Taking into account the potential challenges a robotic system might encounter in a mining setting, this thesis by compendium introduces a scaled, conceptual model of a larger mine-ready robotic system. The goal is to explore the principles of modularity, self-assembly, and adaptability in unstructured, subterranean mining environments. In particular, **P.I's** main contribution is the description of the overall robotic system, as well as the kinematic modeling of the mobile platform and the validation tests of the different robotic concepts.

4.1.2 Hardware description

The robotic system is composed of a modular architecture of heterogeneous robotic modules that can share energy, self-assemble, and be highly configurable through its module and submodule coupling system. Within the robotic system, the main component consists of a main mobile platform (Figure 4.3), named RM2, which houses three compartments and three docking ports dedicated to each of its robot legs. The electronic components are mainly located within the compartments and internal structure of the robot. Meanwhile, the docking ports function as versatile interfaces for assembling various end effectors, such as screws, tracks, and cameras, adapted to the specific task at hand. Additionally, the module includes a coupling mechanism based on a soft robotic arm that enables automatic reconfiguration during operation. A detailed description of the design and functionality of the arm and the sensing module are presented in publications **P.II** and **P.III**, respectively.

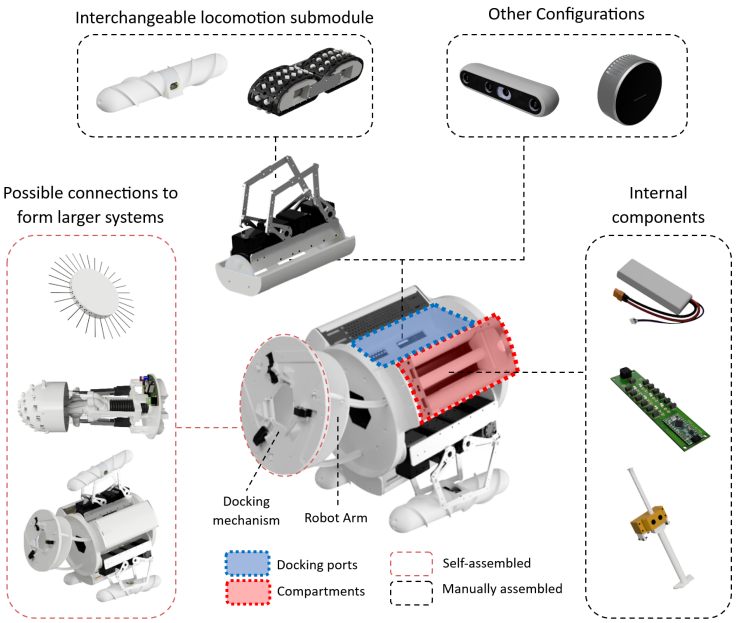


Figure 4.3: Description of the RM2 Robotic System: Each individual robotic module is equipped with three compartments and three docking ports. These versatile docking ports are used to configure a range of locomotion submodules or integrate additional sensors. The compartments house various internal components, while the robot arm facilitates the coupling of different modules, enabling the formation of more intricate and complex robotic systems.

Since the prototype presented is a scaled version of a future robotic miner, it was decided to use low-cost Commercial Off-the-Shelf (COTS) mechanical and electronic components to ensure rapid integration and repairability of the modules. For the actuators, it was decided to use multi-turn Dynamixel servomotors for the leg and coupler arm mechanism. High-torque DC motors were selected for the locomotion submodules and the cutting module. Finally, linear actuators were integrated into the design of the cutting module to guide the cutting head with the parallel mechanism. Regarding electronics, a series of printed circuit boards (PCBs) was designed to manage different aspects of the modules to ensure modularity. For the RM2 module, a power board and a main board were designed to manage the power sharing capabilities and the overall communication and control system of the modules. For the locomotion submodules, electronic boards were designed to control each locomotion system and communicate with the main board. For the sensing and cutting modules, specific boards were designed to control each system, including a power and communication interface to the main board. The technical specifications of the robotic module and the communication protocols implemented are described in detail in **P.I**.

4.1.3 RM2 module leg mechanism

Considering that robotic modules operating in underground mines must be able to traverse irregular terrains, a 5-bar, planar parallel mechanism was designed to control the position and orientation of the locomotion submodule, allowing greater adaptability to unstructured terrains and different locomotion methods. The design also helps reduce the robot's footprint, making it suitable for

deployment in robotic mines through boreholes.

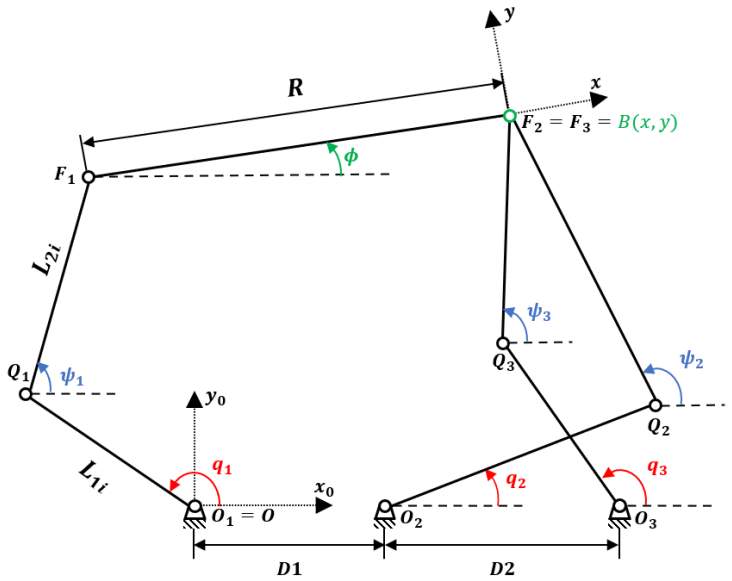


Figure 4.4: RM2 Leg mechanism mechanical model. The motor input angles q_1, q_2 and q_3 are presented in red, while the resulting position of point of interest $B = (B_x, B_y)$ and orientation ϕ is in green. The relative angles between links L_{1i} and L_{2i} are represented in blue.

An analytical representation of the proposed mechanism is presented in Figure 4.4, where the position of point B of the platform is controlled by a 5-bar planar link ($O_2Q_2BQ_30_3$), and the orientation (ϕ) by a 4-bar link (O_1Q_1FB). Furthermore, the mechanism can rotate on the x axis of the leg, providing the robot with an additional DoF, controlled by the front motor.

The origin of the mechanism O is defined along the first motor axis, where x_0 goes along the vector O_1O_3, resulting in $x_{O1} = y_{O1} = y_{O2} = y_{O3} = 0$. The lengths of the O_iQ_i and Q_iF_i links are indicated by L_{1i} and L_{2i}, and the dimension of the platform F_1B is indicated by R. Therefore, considering the geometry of the mechanism, the following relationship is derived.

$$\overrightarrow{OB} = \begin{bmatrix} B_x \\ B_y \end{bmatrix} = \begin{bmatrix} x_{O_i} + L_{1i}\cos q_i + L_{2i}\cos\psi_i + x_{F_iB} \\ y_{O_i} + L_{1i}\sin q_i + L_{2i}\sin\psi_i + y_{F_iB} \end{bmatrix} \tag{4.1}$$

Rearranging equation 4.1 and squaring both sides, the following expression is obtained:

$$g_i = (x - x_{F_iB} - x_{O_i} - L_{1i}\cos q_i)^2 + (y - y_{F_iB} - y_{O_i} - L_{1i}\sin q_i)^2 - {L_{2i}}^2 = 0 \tag{4.2}$$

Expanding the expression in equation 4.2, the following system is defined:

$$g_1 = (x - R\cos\phi - L_{11}\cos q_1)^2 + (y - R\sin\phi - L_{11}\sin q_1)^2 - {L_{21}}^2 = 0 \tag{4.3}$$

$$g_2 = (x - x_{O_2} - L_{12}\cos q_2)^2 + (y - L_{12}\sin q_2)^2 - {L_{22}}^2 = 0 \tag{4.4}$$

$$g_3 = (x - x_{O_3} - L_{13}\cos q_3)^2 + (y - L_{13}\sin q_3)^2 - {L_{23}}^2 = 0 \tag{4.5}$$

Due to the decoupling properties of the robot leg, the forward kinematic problem is solved following two main steps. First, the position of point B is expressed as a function of angles q_2 and q_3, solving the system formed by equations 4.4, and 4.5.

$$B_x = \frac{-\Big((e_3 - e_2)\,B_y + (f_3 - f_2)\Big)}{d_3 - d_2} \tag{4.6}$$

$$B_y = \frac{-v_1 + \sqrt{v_1^2 - 4u_1w_1}}{2u_1} \tag{4.7}$$

Finally, the angle of inclination ϕ is found by substituting equations 4.6 and 4.7 into 4.3, resulting in the expression presented in equation 4.8. The variables e, f, v and w are relationships between the input angles and lengths of the links of the mechanism. The complete derivation of the solutions can be found in **P.I**.

$$\phi = 2\tan^{-1}\left(\frac{-v_2 - \sqrt{v_2^2 - w_2^2 + u_2^2}}{w_2 - u_2}\right) \tag{4.8}$$

For the inverse kinematics model of the mechanism, given the generalized expression from equation 4.2 and solving for q_i, the resulting expression is found:

$$q_i = 2\tan^{-1}\left(\frac{-b_i \pm \sqrt{b_i^2 - c_i^2 + a_i^2}}{c_i - a_i}\right) \tag{4.9}$$

Where again the variables a_i, b_i, and c_i presented in equation 4.9 are relationships between the lengths of the mechanism links and the position and orientation of point B. It should be noted that the two possible solutions from the expression depend on how the mechanism works, based on the elbow position in the pair of links L_{1i} and L_{2i}. For the selected configuration, presented in Figure 4.4, angles q_1 and q_2 considered the "–" solution, while q_3 considered the "+" solution.

To obtain the resulting workspace of the mechanism, a singularity analysis is carried out, analyzing the input and output speeds, which are, the platform twist $\dot{x} = \left[\dot{B}_x, \dot{B}_y, \dot{\phi}\right]^T$ and the vector of articular velocities $\dot{q} = [\dot{q}_1, \dot{q}_2, \dot{q}_3]^T$. By deriving the resulting system of equations presented in Equations 4.3 through 4.5, the relationship between input and output coordinates can be defined, where A and E are Jacobian matrices of n x n.

$$A\dot{x} + E\dot{q} = 0 \tag{4.10}$$

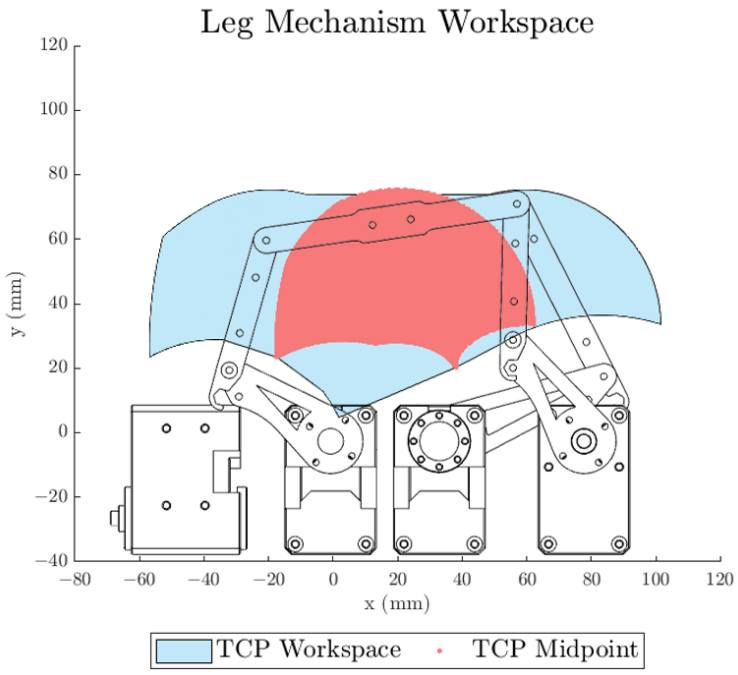


Figure 4.5: RM2 Leg mechanism resulting workspace.

Singularities occur in configurations where A or E become singular, i.e. their determinant is zero. Analyzing equation 4.10, there are three scenarios in which this could happen, with their respective physical interpretations. The first case occurs when E becomes singular. This case arises when the segments O_iQ_i and Q_iF_i are collinear. The second type of singularities ($\det(A) = 0$) appears if the segments F_1B and Q_1F_1 or the segments Q_2F_2 and Q_3F_3 are collinear. Finally, the third case occurs when both A and E become singular at the same time. This condition usually depends on the design of the mechanism, and in this case, no singularity was detected. After evaluating and filtering each edge case for the range of motion of each actuator, the resulting safe workspace of the leg mechanism is shown in Figure 4.5, where the blue region represents the workspace of the mechanism for the final link and the dots represent the midpoint position of the final link.

4.1.4 Robotic system configuration and locomotion experiments

The experimental tests carried out with the RM2 platform in **P.I** are designed to demonstrate the concepts of reconfigurability and evaluate the functionality of the designs of the different system submodules. Some examples of achievable configurations are presented in Figure 4.6, where two RM2 modules are assembled to form larger robotic structures capable of performing more complex tasks, such as mining.

To validate the locomotion capabilities of the module, a slope climbing test was carried out for the two different locomotion submodules developed for RM2 mobile modules. Figure 4.7 shows an overview of the test, where the slope was increased until the robotic module failed. Both configurations were able to consistently overcome slopes of 25º. In addition to these tests, several experiments that validate omnidirectional locomotion of screw and track modules , and other modules integration and mission execution examples can be consulted in Gomez, Hernando, et al., 2023.

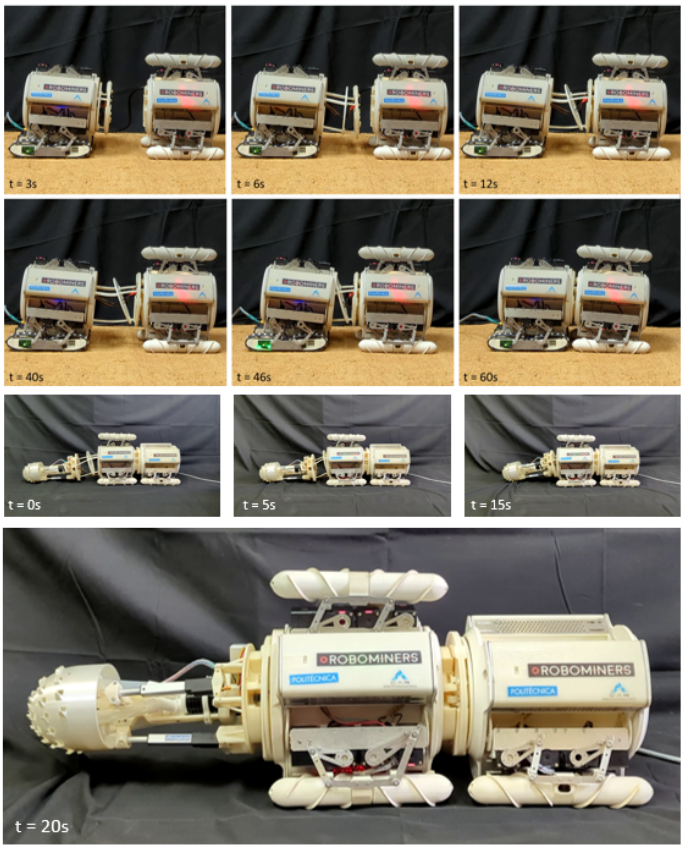


Figure 4.6: Reconfigurability tests for the RM2 robotic modules with different locomotion submodules

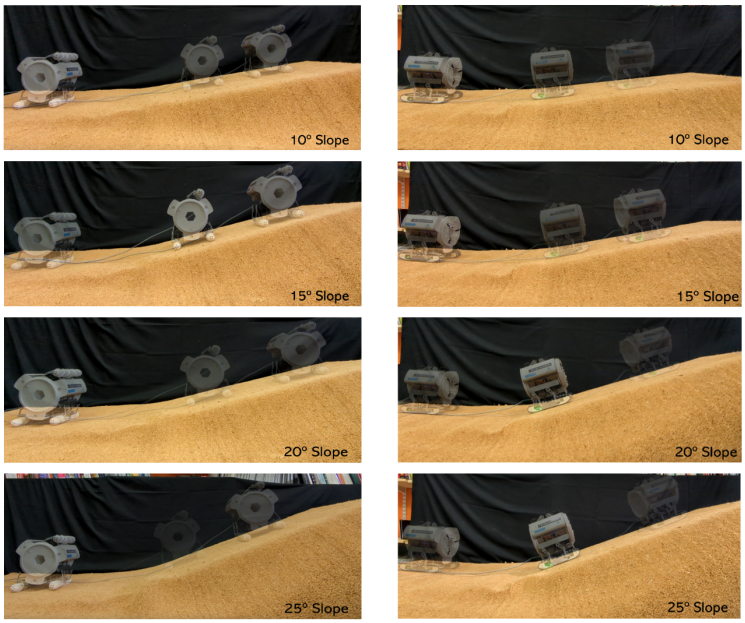


Figure 4.7: Slope climbing test for different locomotion submodules. On the left, the RM2 module features screws, while on the right uses track wheels.

4.2 Soft Robotic Coupling Mechanism for Modular Robots (Publication P.II)

Publication **P.II** presents the design and development of a novel coupling mechanism for modular robots based on a telescopic soft robotic arm. The RM2 Coupling Mechanism (RM2CM) comprises a compact and fully retractable soft robotic arm that serves as the self-assembly mechanism (**O.2**) of the robotic module presented in **P.I**. The article provides a detailed description of the arm, including the actuation principle (**O.2.1**) and material selection process. The resolution of the kinematic problem is presented using a combination of analytical and data-driven methods (**O.2.2**). To verify and validate the proposed models, a series of prerecorded sequences are evaluated. Finally, a set of coupling maneuvers are executed to demonstrate the functionality of the arm as a soft coupling mechanism for modular robots (**O.4**).

4.2.1 Introduction

Implementing a robust and efficient coupling mechanism that allows robotic modules to reach and attach other modules plays a crucial role in realizing the full potential of modular robotic systems, particularly in demanding environments such as underground mining sites. The use of traditional robot arm designs embedded in the robot structure as coupling mechanisms has been a common approach. However, this solution often leads to increased complexity and bulkiness in the robotic system, limiting its flexibility and adaptability. Additionally, traditional coupling mechanisms, such as mechanical connectors or latches, face notable challenges in harsh mining environments characterized by unpredictability and variability.

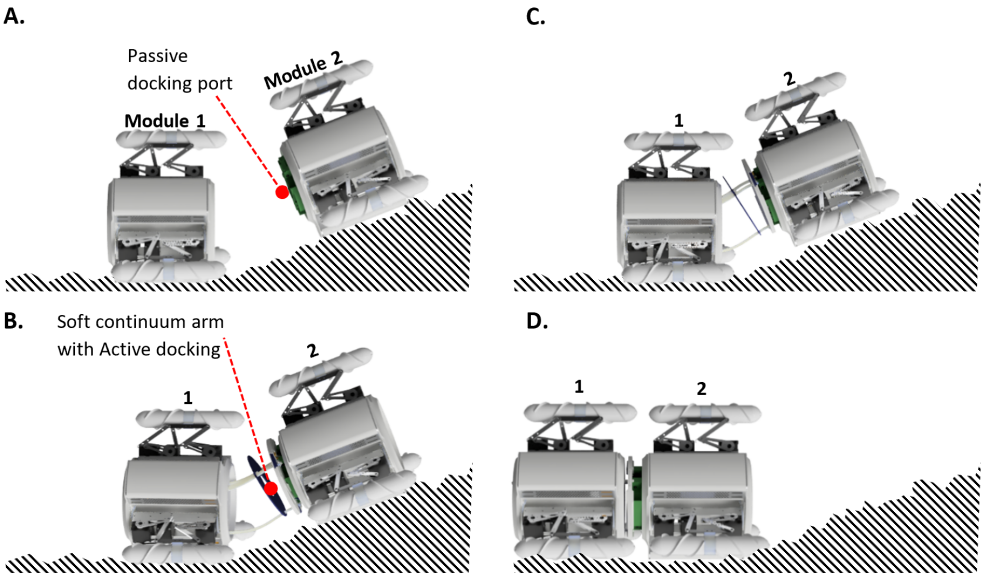


Figure 4.8: Soft Continuum arm as coupling mechanism. (**A**) Car crane principle for docking robots or tool modules. (**B**) First, the soft continuum arm is guided to the module/tool docking port. (**C**) Then, the end effector docking mechanism secures the module/tool. (**D**) Finally, the arm is retracted back to the module securing and attaching the desired part. ©2023 Mary Ann Inc

To address these limitations and enhance the functionality of modular mining robots, there is a need for innovative solutions. One promising approach involves the integration of soft continuum arms as coupling mechanisms. By incorporating soft continuum arms, modular mining robots can better adapt to the dynamic conditions of unstructured mining environments (Figure 4.8).

In response to the identified challenges, **P.II** introduces a novel approach in the form of a soft continuum arm that serves as a coupling mechanism for modular robots. The arm explores the concept of car cranes to result in a highly adaptable arm with high mass-pulling capabilities. This mechanism leverages the inherent capabilities of continuum arms to facilitate efficient coupling between robotic modules. In doing so, the goal is to address the shortcomings of traditional coupling methods while maximizing the adaptability and performance of modular mining robots.

4.2.2 Hardware description

To provide the modular robotic system with the ability to reconfigure during operation, it is necessary to design a compact and robust solution that allows the coupling of different robotic modules without the need to be in close contact or aligned. Taking this into account, the arm, shown in Figure 4.9 was designed by drawing inspiration from the working principle of a car crane, where the arm can be easily guided into a docking port of another robotic module, secured, and then pulled back with force.

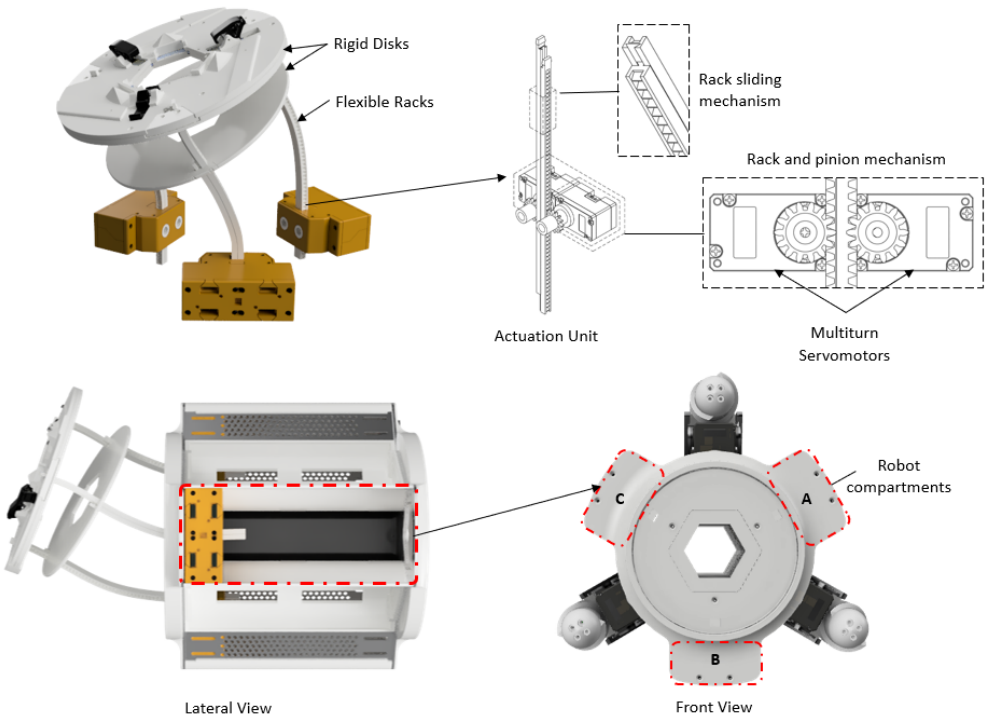


Figure 4.9: Hardware Description of the Soft Robotic Arm in the Modular Robotic Prototype. The arm showcases a composition of flexible racks, rigid disks, and servomotors integrated into the robot's frame.

The arm design followed an iterative process, starting with a 2D version to validate the arm actuation principle and telescopic capabilities. In tandem, a material selection process was conducted to determine which 3D-printing filament would be the most suitable for soft racks, where TPU 95A was found to be the best option. After refining and correcting some minor issues in the design of the soft racks, the design was scaled up to its current form, where 3 Actuation Units (AU) were installed in a common base, resulting in a 5 DoF soft continuum manipulator. Due to the innovative nature and scalability of the mechanism design that drives the arm, a patent was granted (Hernando et al., 2022).

The coupling mechanism (Figure 4.10) consists of a set of evenly spaced claws and profiles driven by a high-torque DC micromotor and a crown gear mechanism. The claws are based on an underactuated 4-bar mechanism that converts the linear motion of the claw base into an enveloping motion that helps capture the passive port. Once the passive port is gripped by the claws, the T-profiles provide a strong connection between the modules. To ensure successful assembly and achieve the goals of power sharing and modularity, three equally spaced magnetic connectors are installed to provide a power connection and a communication channel between the modules, sending feedback and identification of the attached module.

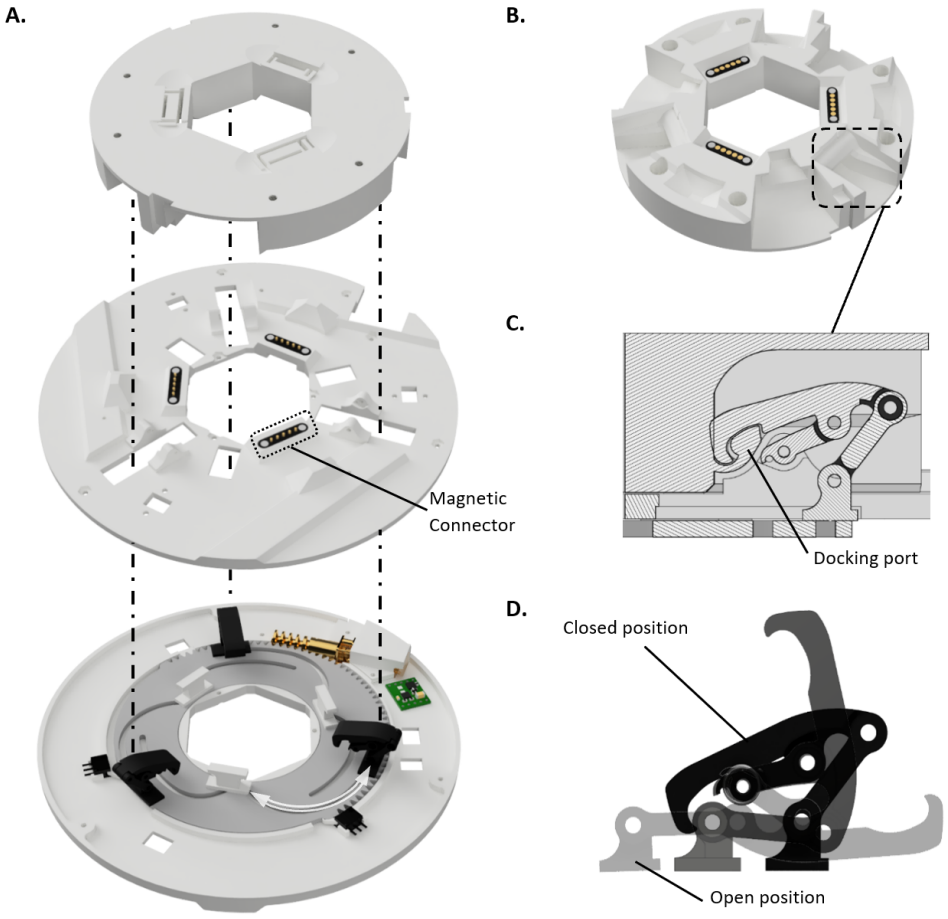


Figure 4.10: Coupling mechanism hardware description. ©2023 Mary Ann Inc

4.2.3 Soft Continuum arm modeling

The modeling of a soft continuum arm is a challenging task due to the nonlinearities that result from the bending and torsional effects present in deformable materials. Different approaches are commonly used to solve continuum arm kinematics, where according to George Thuruthel et al., 2018, virtual backbone parameterization using constant curvature (CC) or piecewise constant curvature (PCC) models is the most common approach for forward kinematics. In contrast, data-driven methods that use neural networks are among the most widely used approaches for the inverse model (Xu et al., 2017).

4.2.3.1 Forward kinematics

Considering that the robotic arm exhibits a nearly constant curvature and that the bending of each section is independent, a CC model was adopted to solve the direct kinematic problem. By transforming the motor input into the corresponding rack extensions (l_1, l_2, l_3), taking into account the radii of the sections d and using the George Thuruthel et al., 2017 model, the arc parameters (r_i, ϕ_i, θ_i) are determined for each section by substituting rack values and section radii in equations 4.11, 4.12, and 4.13. It is important to note that the extension for the second section is calculated by subtracting the length of the first section from the total lenght extension of the paired racks.

$$r_i = \frac{(l_1 + l_2 + l_3)\, d}{2\sqrt{{l_1}^2 + {l_2}^2 + {l_3}^2 - l_1 l_2 - l_1 l_3 - l_2 l_3}} \tag{4.11}$$

$$\phi_i = atan2\left(\frac{l_2 + l_3 - 2l_1}{\sqrt{3}\,(l_2 - l_3)}\right) \tag{4.12}$$

$$\theta_i = \frac{2\sqrt{{l_1}^2 + {l_2}^2 + {l_3}^2 - l_1 l_2 - l_1 l_3 - l_2 l_3}}{3d} \tag{4.13}$$

Once the arc parameters are obtained, the homogeneous transformation matrix T can be calculated for each of the arm sections by solving the equation 4.14. Lastly, the arm's tip pose can be determined by multiplying the section's transformation matrices in order from the base to the tip. The derivation of the matrix can be found in the publication.

$$T\,(r_i, \theta_i, \phi_i) = \begin{bmatrix} c_\phi^2 c_\theta + s_\phi^2 & c_\phi s_\phi\,(c_\theta - 1) & c_\phi s_\theta & r c_\phi\,(1 - c_\theta) \\ c_\phi s_\phi\,(c_\theta - 1) & s_\phi^2 c_\theta + c_\phi^2 & s_\phi s_\theta & r s_\phi\,(1 - c_\theta) \\ -c_\phi s_\theta & -s_\phi s_\theta & c_\theta & r s_\theta \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.14}$$

4.2.3.2 Inverse kinematics

For the inverse kinematic problem, a data-driven approach was followed by implementing a machine learning algorithm. To learn the kinematic model, a data gathering process was first carried out to capture the arm's tip pose by using a fiducial marker and a camera system. The rack extension using the servomotors built-in encoders and the transmission relationship for the rack-pinion mechanism.

A more detailed description of the process is presented in the article, where a follow-up step consisted of tuning and comparing different machine learning algorithms to select the most suitable model. The selected model was an Extreme Learning Machine (ELM) algorithm, given its speed and accuracy.

4.2.3.3 Model Validation

To assess the performance and precision of the presented kinematic models, a set of predefined sequences was tested. Each sequence consists of a maneuver executed three times, each with different orientations at the robot's base, covering a total of 90 points within the robot's operational zone. The first sequence demonstrates the arm's extension and flexion range starting from the home position, where the arm is retracted into the robot, moving towards a specific, final pose. The next sequence traces a triangular path while maintaining a constant elevation.

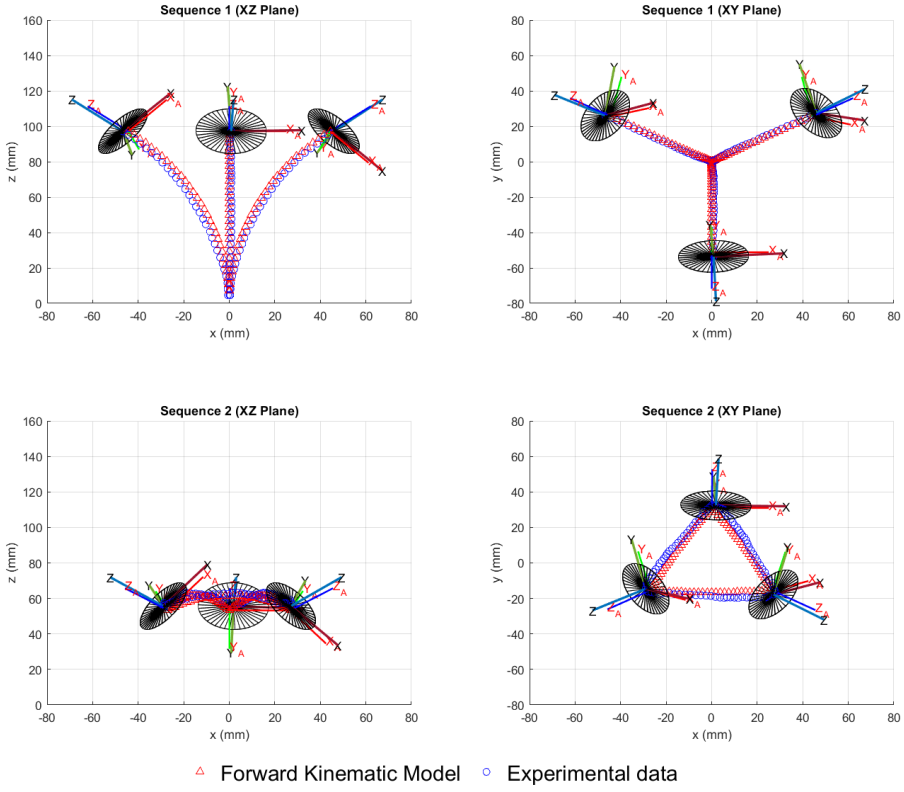


Figure 4.11: Forward kinematic model validation. The red triangles represent the analytical model calculated position, while the blue circles are the ground truth ©2023 Mary Ann Inc

Regarding the forward model, the arm's tip calculated position and orientation, along with the corresponding errors are presented in Figure 4.11 and Tables 4.1 and 4.2. Concerning the error analysis, the position is evaluated using maximum error, mean average error (MAE), and root mean square error (RMSE) as comparison metrics. Converesely, the orientation is evaluated by the minimum rotation angle between the reported and computed quaternions and the dot product, where

a value close to 1 means that the two quaternions represent the same orientation. By analyzing the results, it can be seen that the model accurately represents the behavior of the arm, with a maximum deviation of 4mm for position and 4.31° and a minimum dot product of 0.9993 for orientation, both of which occur in the second sequence. These data points are consistent with the behavior shown in Figure 4.11, where the calculated position and orientation closely match the experimental results.

Table 4.1: Arm tip position estimation error using the direct kinematics model. ©2023 Mary Ann Inc

	Sequence 1			Sequence 2		
	X	Y	Z	X	Y	Z
Max Error (mm)	2.76	2.72	3.13	4.00	3.87	2.87
MAE (mm)	1.07	1.00	1.66	1.73	1.74	1.56
RMSE (mm)	1.27	1.27	1.91	1.99	1.99	1.62

Table 4.2: Arm tip orientation error using the direct kinematics model. ©2023 Mary Ann Inc

		Sequence 1			Sequence 2		
	Units	Min	Avg	Max	Min	Avg	Max
$\angle\left(w, w_{pred}\right)$	deg	1.312	2.358	3.686	1.269	2.252	4.31
$\left(w \cdot w_{pred}\right)$	–	0.9995	0.9998	–	0.9993	0.9998	–

The inverse model was evaluated using identical sequences, by this time focusing on the rack extensions. The results are shown in Figure 4.12 and Table 4.3 and demonstrate the ability of the network to accurately predict the rack extension for each segment, with a maximum total error of 18.24 mm for the initial sequence and 25.7 mm for the subsequent sequence. It is worth noting that both the MAE and RMSE are less than 5 and 6 mm, respectively. The accuracy of the predictions varies in each section, with the rack of the second section typically having a smaller error than the first section for both test sequences.

Table 4.3: Rack extension error using the inverse kinematic model. ©2023 Mary Ann Inc

		Sequence 1			Sequence 2		
	Rack extension	MAX	MAE	RMSE	MAX	MAE	RMSE
Section 1	l_{11}	12.95	4.18	5.07	22.80	3.57	4.59
	l_{21}	11.46	3.43	4.04	25.70	4.51	5.64
	l_{31}	16.96	4.57	5.72	24.84	4.69	5.88
Section 2	l_{12}	10.61	4.04	4.94	12.99	3.65	4.71
	l_{22}	11.12	3.81	5.06	14.82	3.62	4.54
	l_{32}	18.24	3.68	5.06	11.82	3.78	4.66

All reported values are in mm

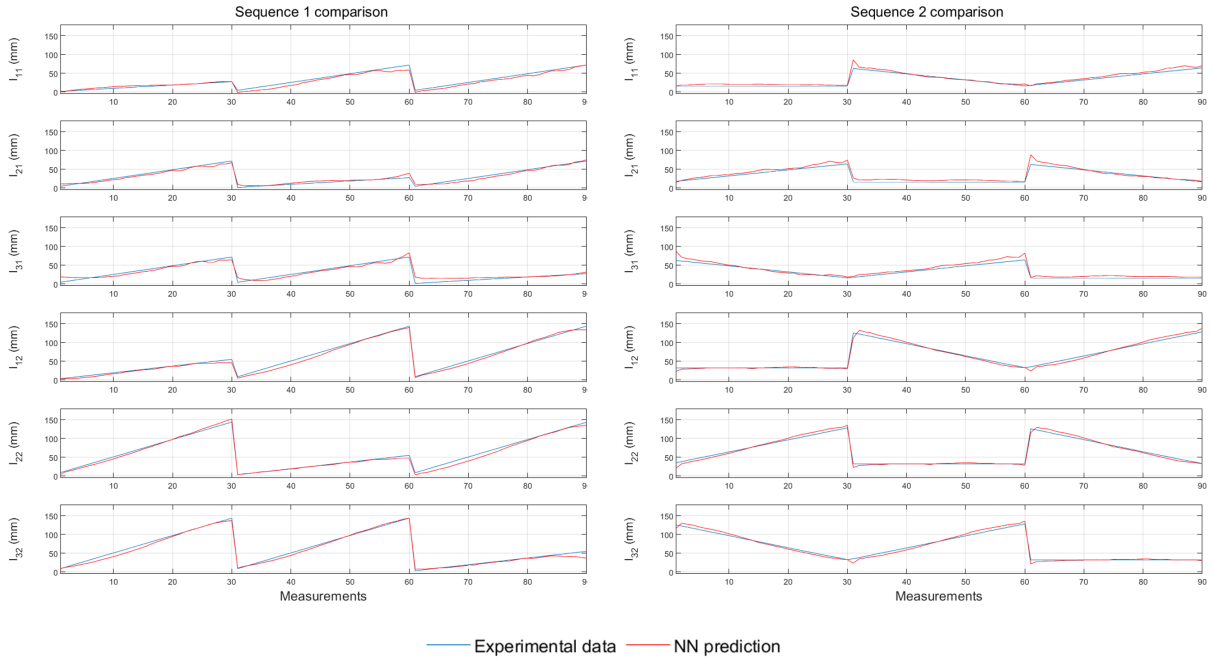


Figure 4.12: Inverse kinematic model validation. The red line represents the prediction of the ELM network, while the blue one represent the rack extension in mm. ©2023 Mary Ann Inc

It should be emphasized that the two models discussed in **P.II** did not take into account the effect of the weight at the end of the arm, regarding the curvature in bending sections. This aspect was taken into account in a later development, as shown in Appendix B, where a data-driven method was used for both forward and inverse kinematic models.

4.2.4 RM2 coupling experiments

The tests conducted in **P.II** were focused on assessing the validity of the proposed solution for different scenarios to ensure that the robotic system can be reconfigured during operation, satisfying objectives **O.2** and **O.4**. The tests consisted of performing two assembly procedures between two robotic modules on a straight and curved trajectory, as shown in Figure 4.13. For the execution of the maneuver, the position of the second module was fixed and kinematic models were used to determine the final actuator values. It was decided to add some waypoints to generate a safe trajectory for the arm to perform the coupling maneuver.

The tests yielded successful results, validating the high mass pulling capability of the mechanism and the validity of the kinematic models, ensuring that the arm can be controlled and guided to other robotic modules to perform the coupling maneuvers. It should be noted that these were the first results on a work in progress development that has been further advanced, as shown in Appendix B.1, where a camera module was added to provide the module with the capacity to identify where the second module is located to then perform the coupling maneuver.

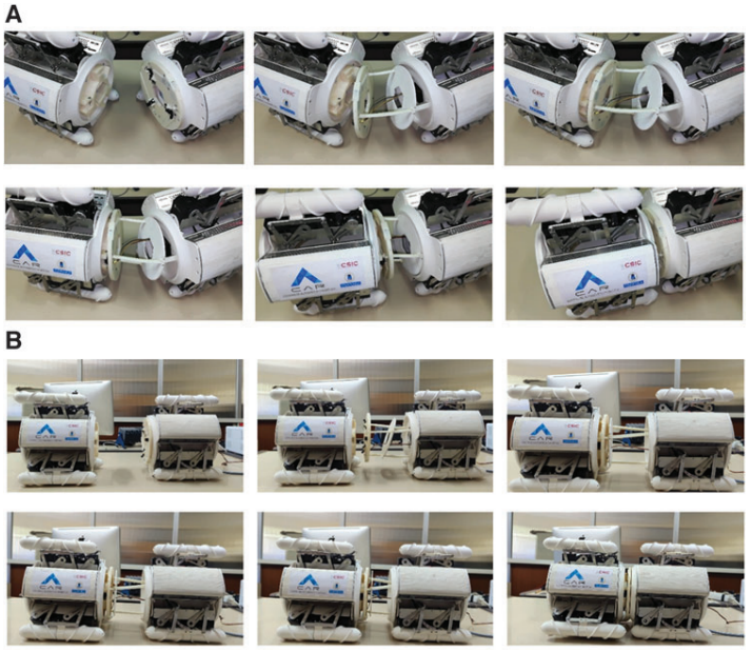


Figure 4.13: Module coupling maneuvers: (a) Following a curved trajectory. (b) Following a straight trajectory. ©2023 Mary Ann Inc

4.3 Whisker-based sensing module for environment reconstruction (Publication P.III)

In **P.III**, the focus lies on the design (**O.3.1**), sensor modeling (**O.3.2**), and experimental validation of the sensing module within the modular robotic system presented in **P.I**. The article begins by detailing the sensor components and the manufacturing process involved. Consequently, the sensor model is developed following analytical and data-driven methodologies. Then, a series of experiments is conducted to validate and compare these models. Upon identifying the most effective model, a 3D-mapping experiment is performed to evaluate both the model's accuracy and the sensor's design suitability. It is worth mentioning that, for a more robust assessment, the sensor was initially tested on an industrial, serial manipulator to minimize positional errors originating from the robot arm discussed in **P.II**. The module was later tested in the robotic module, as shown in the Appendix B.2.

4.3.1 Introduction

Autonomous robots face a multitude of challenges when navigating underground mining environments, including high dust concentration, uneven terrain, limited light sources, geolocation restrictions, and difficult communication. These factors hinder the effectiveness of conventional and robust localization and mapping technologies that rely on Global Positioning Systems (GPS), cameras, and LiDAR sensors (Lopes et al., 2020). In such scenarios, alternative sensory solutions such as whisker-based sensors have emerged as a robust, straightforward, and accurate option for obstacle avoidance and SLAM tasks (Milford et al., 2004; Salman and Pearson, 2016b). Despite the clear versatility of whisker sensors, demonstrated in their use for various tasks, such as object

localization, contour and texture detection, fluid flow direction, and viscosity measurement, there is limited exploration in their application for environmental reconstruction tasks. The task of mapping 3D spaces introduces further complexities, given that whisker-based sensors are required to efficiently maneuver and decode spatial data. Elements like environmental variations, surface patterns, and the demand for instantaneous adaptability add to the complexities encountered when creating robust models for whisker-based sensors in 3D-mapping scenarios.

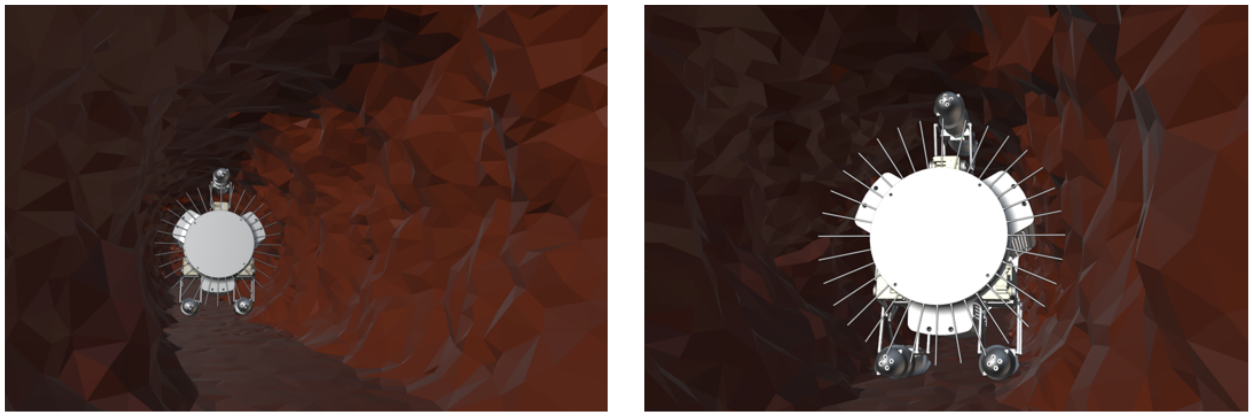


Figure 4.14: Conceptual implementation of the whisker disc for enhancing the RM2 module navigation and mapping capabilities in underground mining environments.

Given the potential of the modular robot prototype presented in **P.I** to reconfigure during operation and perform different tasks, such as mining or sensing the environment, it was decided to design a scaled version of a sensing module for environment reconstruction tasks (Figure 4.14) drawing inspiration from the naked mole rat, a rodent species recognized for their orientation and navigation capabilities in underground spaces (Park et al., 2010). The disk design tries to approximate a section of the mole rat body, where the sensory hairs are approximately distributed in a ring-like pattern across the whole body. Publication **P.III** presents a whisker-based sensing disk to perform environmental reconstruction tasks in mining environments.

4.3.2 Hardware description

The module comprises a 3D-printed disk where a circular array of 32 whisker sensors is housed. Each whisker is conformed by a central, 3D-printed resin structure named *magnet holder*, where a magnet is attached to its rear end, while at the front has a plastic rod that acts as the whisker. Different materials, such as carbon fiber, glass fiber, ABS 3D-printed rods, and polystyrene rods were tested for the whiskers. Polystyrene rods were selected due to its flexibility and capability to recover its form after large deflections.

To detect when whiskers come into contact with a surface, a 3D hall-effect sensor (Infineon TLV493D) was used for each whisker. The 32 sensors were inserted into a custom circular PCB, while communication was established through an I2C protocol. Since there were more sensors than available I2C directions, four 8-channel multiplexers were added. The working principle is that the sensor captures the magnetic field generated by the magnet in three dimensions, and a sensor model translates this information into the bending angles of the whisker.

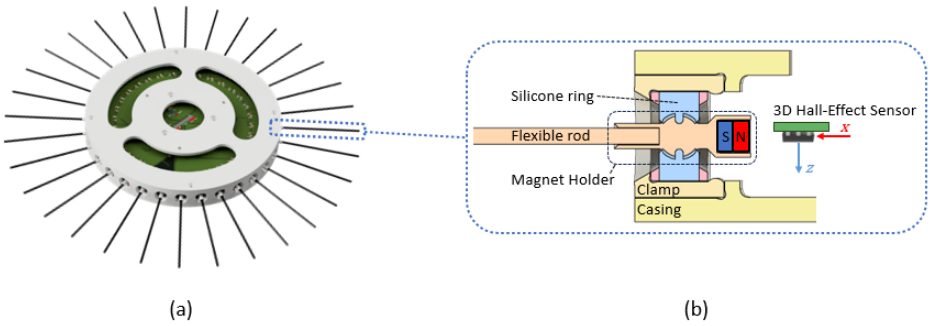


Figure 4.15: Whisker based sensing module description: (a) the sensing disk comprises a circular array of 32 whisker sensors. (b) Single Whisker sensor section view.

4.3.3 Sensor modeling

To estimate the point of contact of the whisker given the magnetic field measurements, two approaches based on analytical and data-driven models were developed and compared. Before the modeling stage, a data capture process was performed to train and calibrate both models. An experimental setup was built where a single whisker was installed in the disk, and a sequence of movements was pre-programmed to capture the whisker workspace, as well as the corresponding values of the magnetic sensor for each position.

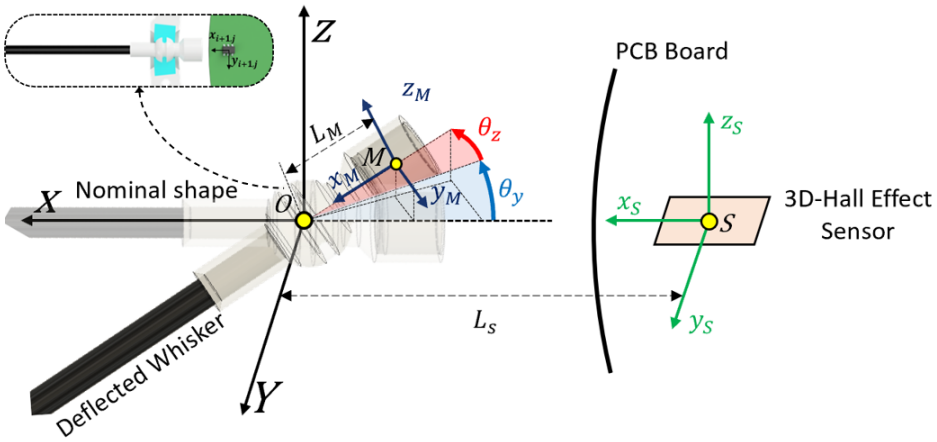


Figure 4.16: Whisker Rotational model: The whisker rotates in two different angles from the pivotal point O, generating a change in the position and orientation of magnet M that is captured by the 3D Hall Effect Sensor S

For the analytical approach, an approximation is presented considering the geometrical relationship between the whisker rotational angles (θ_z and θ_y) and the magnetic field intensity vector $\vec{B} = \begin{Bmatrix} B_x & B_y & B_z \end{Bmatrix}$. The graphical representation of the proposed model is shown in Figure 4.16, where the equations of the whisker rotation model can be derived.

Therefore, the position of the magnet can be estimated by solving Equations 4.15 and 4.16, where sc_{θ_y}, b_{θ_z}, b_{θ_y} and b_{θ_z} represent the scaling and bias factors for both bending angles, respectively.

These factors were adjusted based on empirical data.

$$\theta_z = \frac{atan2\left(B_y, B_x\right)}{sc_{\theta_z}} - b_{\theta_z} \tag{4.15}$$

$$\theta_y = -\frac{atan2\left(B_z, \sqrt{B_x^2 + B_y^2}\right)}{sc_{\theta_y}} - b_{\theta_y} \tag{4.16}$$

For the data-driven model, a machine learning algorithm is implemented to account for the non-linearity and inconsistencies derived from the whisker sensor fabrication process. This approach was considered given the advantages of having a more adaptable solution, with the cost of reducing the explainability of the model. After a model selection process, an Extreme Learning Machine (ELM) algorithm resulted in the best-performing model, given its small response time and accuracy.

4.3.3.1 Model comparison and validation

Six randomly chosen whiskers were evaluated for precision and computational efficiency for both models. The analytical model was fine-tuned for scaling and bias adjustments using an optimization process based on the nonlinear least squares method. Concurrently, the data was used to train an ELM, and a test set containing 200 data points was analyzed for each whisker (see **P.III**).

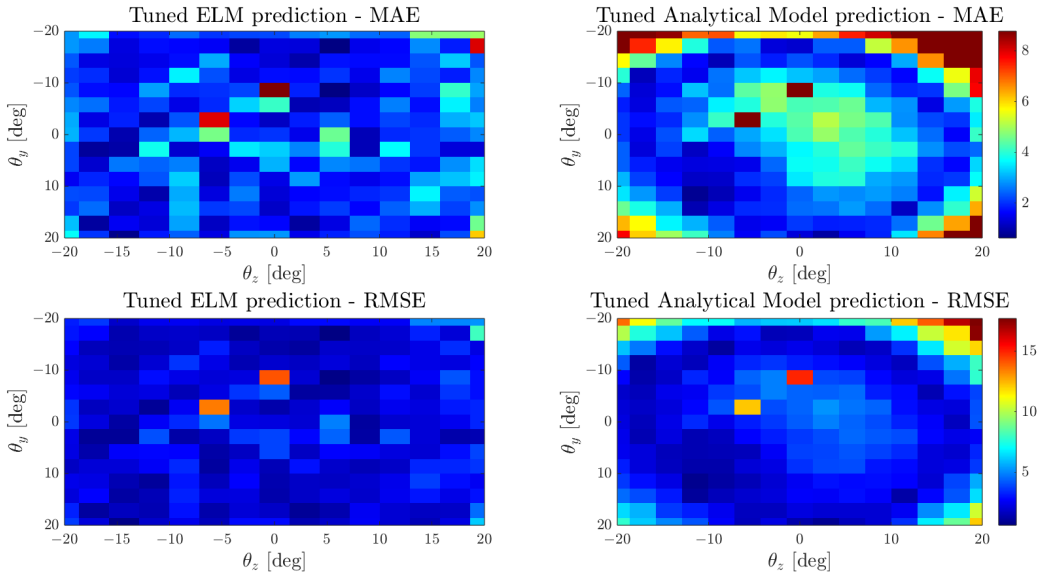


Figure 4.17: Mean average error and root mean square error heatmap comparison between the ELM and analytical models tuned for a single whisker.

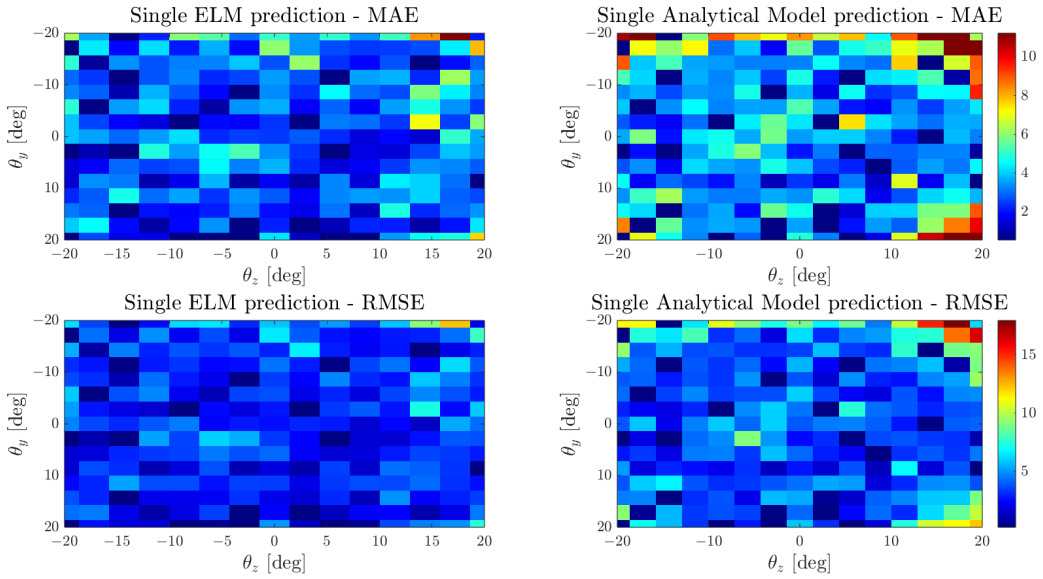


Figure 4.18: Mean average error and root mean square error heatmap comparison between the ELM and analytical models tuned for the whiskers combined dataset.

Following the adjustments to both models, an evaluation was conducted to determine their effectiveness using a dataset for a single whisker (Figure 4.17). The heatmap illustrates the angle prediction discrepancies of these models within the whisker's operational area, showing MAE and RMSE metrics for each cell. Upon comparing the two models, it is observed that the ELM model consistently performs well throughout the entire spectrum of the whisker sensor, whereas the analytical model shows increased errors at greater rotational angles. This indicates that the analytical model struggles with accurate predictions at higher rotational angles, due to the greater influence of nonlinearities in those scenarios.

Table 4.4: Whisker rotation model comparison for general models for the combined whisker dataset.

Rotation	Single ELM (N_hidden_neurons = 30)				Single Analytical Model ($sc_{\theta_z} = 2.37$, $sc_{\theta_y} = 1.75$ $b_{\theta_z} = -0.01$, $b_{\theta_y} = -0.02$)			
Angles	MAE [rad]	RMSE [rad]	R^2	Time [ms]	MAE [rad]	RMSE [rad]	R^2	Time [ms]
θ_z	0.0352	0.0464	0.95	0.18	0.0505	0.0665	0.90	0.87
θ_y	0.0388	0.0537	0.94		0.0589	0.0833	0.84	

To broaden the applicability of the model to all whiskers, a unified general model was created for ease of use. This was achieved by merging all collected whisker data into one dataset. Analytical and data-driven models were refined and assessed using this integrated approach. For the analytical model, bias and scaling adjustments were calculated by averaging outcomes across all whiskers. For the ELM model, it was retrained on this aggregated dataset. A training/testing split of 70/30 was used for the ELM, with the dataset containing a total of 2094 recordings. To confirm the effectiveness

of these models, their predictive capabilities and speed were evaluated using the test set, verifying that the ELM was not trained on this data. Table 4.4 and Figure 4.18 illustrate the comparative performance of both models in simulating a unified single-whisker workspace. Consistent with expectations, the ELM model demonstrated superior performance, exhibiting reduced errors and deviations throughout the aggregated whiskers workspace.

It is essential to remember that the generalized model only represents a dataset of six different sensors, and even though the 32 sensors data were not captured, it results in a fairly accurate prediction for the intended application. In any case, it is strongly advised to implement a single network for each sensor or train a generalized network with the 32 whisker's dataset to ensure robust behavior of the model.

4.3.4 3D-mapping experiments

Following the successful validation and selection of the whisker model, tests for 3D mapping were conducted to assess the capabilities of the sensing disk. In this case, the testing setup included the whisker disk mounted as the end effector on a Universal Robots UR3e manipulator, and a rectangular box was fixed onto a technical table to simulate the basic geometry of a mine. An application was developed using ROS 2 to interface with the UR driver package (Universal Robots, 2023), which facilitated the reading and updating of the manipulator end effector's position, as well as capturing data from the 3D Hall-effect sensors, while displaying the resulting point cloud in Rviz. The position and orientation of the disk in space were determined by its attachment to the UR3e arm.

To read the 3D Hall-effect sensors, an Olimex A64 computer was programmed to run a routine that checked each sensor's functionality before broadcasting the data on an ROS 2 topic. This was done through a custom message that encapsulated the magnetic field measurements of all 32 whiskers in one packet. The topic publication frequency was set at 10 Hz.

A ROS 2 node was developed to capture the custom whisker message and translate it into the whisker tip's spatial position for point cloud generation. The whiskers were modeled as a rigid bar with two rotational joints at their pivot, and the rotation angles were computed based on the whisker rotational model. A filtering mechanism was established to exclude non-deflected whiskers from the point cloud publication. This mechanism required that the sum of the squares of the rotation angles exceed a predefined threshold. This threshold, set at 0.09 through empirical testing, provided optimal results.

A sequence of 3D-mapping experiments was conducted by remotely operating the robot arm to confirm that the whiskers touched the mapped surface. The mapping technique is illustrated in Gomez, Walid, et al., 2023, and Figure 4.19 shows the 3D-mapping method by creating a point cloud from bent whiskers. This method proved effective in identifying the environment's shape and rough geometry. Further experiments were conducted, with data subsequently exported and processed. To assess the map's precision, the resulting point cloud was analyzed using a clustering algorithm and a filtering algorithm based on the Mahalanobis distance to remove outliers, specifically points far from each cluster, indicating misreadings from whisker vibrations that shifted the PCB board, which suggests whisker deflection.

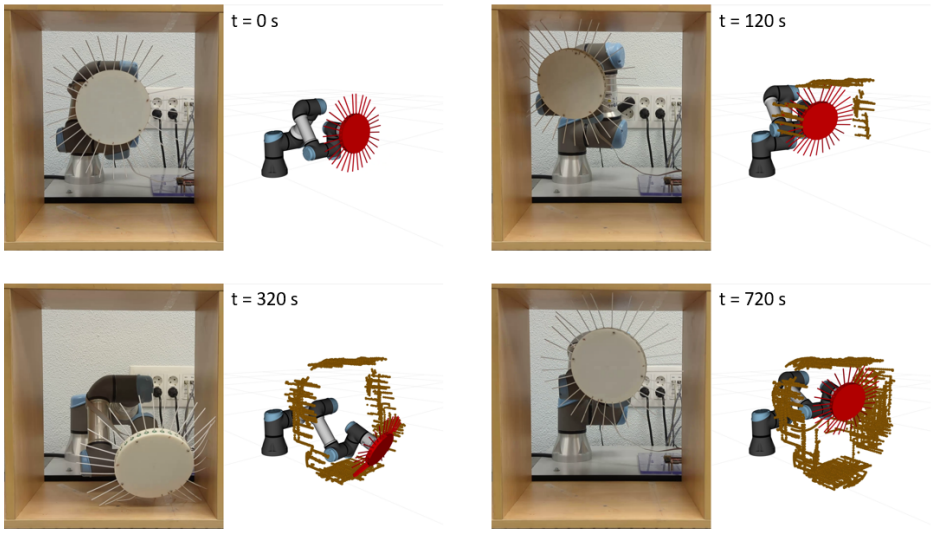


Figure 4.19: Environment reconstruction from the 3D-mapping experiment.

Figure 4.20 and Table 4.5 show the results of the filtered point cloud, validating the accuracy of the proposed method with average errors nearly at millimeter level on most surfaces. To calculate the distance discrepancies for each surface, points were projected onto the nearest surface of the box, and the Euclidean distances between point pairs were computed. The estimated dimensions of the box are 42.74 cm × 46.42 cm × 29.11 cm, which closely match the actual dimensions of 40 cm × 45 cm × 28 cm.

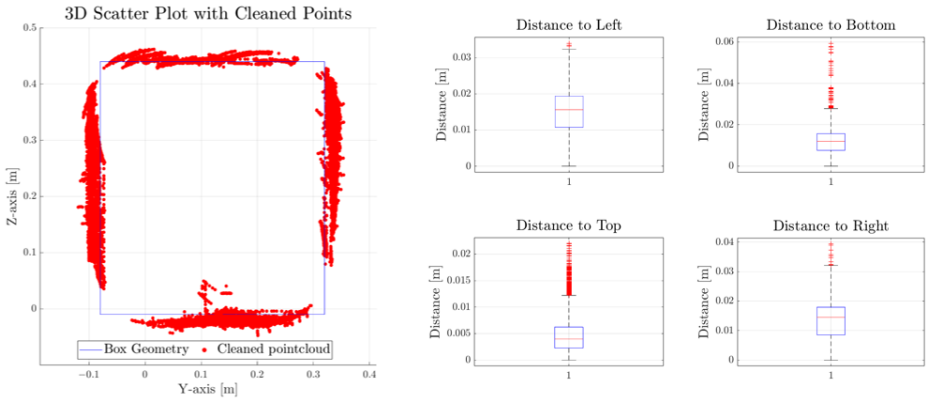


Figure 4.20: Processed point cloud analysis

Table 4.5: Maximum and average errors derived from the post-processed point cloud and the projected points onto the adjacent box surface.

Box Inner Surface	Max Error [m]	Mean Error [m]
Left	0.339	0.0149
Right	0.0394	0.0132
Top	0.022	0.0052
Bottom	0.0593	0.0123

Chapter 5

Conclusions

"The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but 'That's funny...' "

– Rita Levi-Montalcini

This thesis by compendium introduced an innovative, highly adaptable, modular robotic mining system that can reconfigure itself during operation to create larger and more complex structures to perform various challenging tasks. This encompassed the design and development of several robotic modules, including mobile platforms along with conceptual cutting and sensing modules, which can be interconnected through an innovative coupling mechanism utilizing a telescopic, soft continuum arm. The proposed solutions have been tested and validated through several experiments, showcasing their effective performance and functionality. Additionally, this thesis introduced methods and platforms that advance the state-of-the-art and can be expanded to larger systems appropriate for mining settings. It is essential to remember that while the conceptual solutions require further development, the underlying principles are fully applicable and scalable.

Chapter 1 introduced the main objective of this doctoral thesis: *to conceptualize and prototype a suite of innovative technologies that explore modularity, resilience, and reconfigurability in platforms designed for underground mining environments, advancing them to a Technology Readiness Level 4 (TRL-4) to lay the groundwork for future mine-ready systems.* The thematic consistency across publications (**P.I** – **P.III**) highlighted significant progress in the proposed solutions and results, contributing to the overall objective of this thesis. In **P.I**, the overview of the modular robotic system for mining environments was introduced, including a brief description of the key components of the modular system. This included the development of a 4-DoF terrain-adaptive mechanism that allows for the quick configuration of different locomotion submodules suited for underground mining environments, such as Archimedean screws and omnidirectional tracks. Furthermore, **P.I** showcased potential configurations that the robotic system can adopt to carry out numerous tasks, made possible by the adaptable coupling mechanism. In **P.II**, a comprehensive description regarding the development of the self-assembly mechanism for the module introduced in **P.I** is provided. The presented prototype features a 6-DoF soft continuum arm, integrated into the structure of the mobile module. This arm functions similarly to a car crane, allowing the robot to easily guide the coupling head into a passive coupling interface within the structure of other robotic modules. The robot then secures and pulls the second robotic module with force to complete the self-assembly process. To control the arm's position, both analytical and data-driven methods were developed to

model the arm's forward and inverse kinematics. The accuracy of the models was confirmed by comparing preprogrammed maneuvers with the models' predictions, yielding successful results for the intended application. The arm's functionality was validated by performing multiple coupling maneuvers between two robotic mobile modules. Finally, **P.III** introduces the sensing disk module to demonstrate its ability to perform 3D-mapping tasks in underground mining environments. To collect training data for the proposed sensor model and also assess the sensing head design, an industrial manipulator was utilized, which ensured the positioning of the end effector during the sensor model training. After validating the design, the prototype was successfully tested on the robotic platform from **P.I**, integrated into the soft continuum arm (**P.II**) to serve as an active sensing mechanism, with the results documented in Appendix B.

As discussed in Sections 4.1 – 4.3, all the proposed objectives **O.1** – **O.4** (detailed in Section 1.2) were addressed in publications (**P.I** – **P.III**). The main contributions (**C.1** – **C.6**), outlined in Section 1.3, are identified in the following publications: Contributions (**C.1** – **C.4**) were included in Publications (**P.I** – **P.II**), while Contributions **C.5** and **C.6** were presented in **P.III**. Contributions **C.1**, **C.3**, and **C.5** are highlighted as the primary contributions of this dissertation, where the set of prototypes that make up the modular robotic system for mining operations is designed, developed and validated in a laboratory setting to explore the potential of innovative robotic concepts that can be scaled up and implemented in a future mine-ready platform.

The presented reconfigurable modular robotic system for mining operations has undergone thorough verification and validation in an appropriate laboratory setting. The findings, detailed in Chapter 4, indicate that *the development of a highly configurable modular robotic system shows significant promise for deployment in a mining environment, due to its inherent flexibility, adaptability, and ability to accomplish various complex tasks in a resilient manner.*

As indicated by the TRL definitions in Table 3.2, achieving a hardware and software TRL–4 involves demonstrating system performance through representative experiments in a laboratory environment. The solutions developed go beyond the current state of the art and are primarily in the research phase. However, they have been validated under challenging requirements and constraints and have yielded significant, industrial results and insights. Moreover, a technological patent has been granted for the proposed arm actuation mechanism, further confirming the industrial viability of the concepts studied.

5.1 Future Work

In the current state, not all robotic modules have been adapted to be validated in a more relevant environment. Based on the experiences and lessons learned from the results obtained during the development of this doctoral thesis, future work will focus primarily on several research lines that aim to evolve the current design to a more autonomous and resilient system. The first research line involves the development, implementation, and testing of a decentralized, control architecture to orchestrate RM2 modules, with the goal of collaborating to accomplish tasks autonomously. Furthermore, the integration of high-level metacontrol architectures, such as those developed in Aguado et al., 2021, will improve the fault tolerance capabilities of the system for resilient operation. In tandem, the development of modular prototypes will continue on, by designing new modules and locomotion submodules, optimizing connection interfaces, improving the energy-

sharing mechanisms between robotic modules, and lowering overall power consumption to increase endurance and autonomy. Finally, research and development efforts will be directed towards raising the maturity scale of the robotic system to a TRL-5 in the near future.

Therefore, the findings of this thesis, along with the continuous development efforts, mark a crucial advancement towards the goal of developing fully autonomous, modular robotic miners. These miners aim to extract raw materials from underground mines safely, cost-effectively, and with environmental responsibility.