International Journal of Scientific Engineering and Science
Volume 8, Issue 9, pp. 60-70, 2024.
ISSN (Online): 2456-7361

Force-Sensitive Gripper for Autonomous Manipulation in Unstructured Space Environments

Serdar Kalaycioglu[1,2], Jackson Ding[2], Jeric Jiang[2], Brandon Chow[2], Haipeng Xie[2]
[1]Department of Aerospace Engineering, Toronto Metropolitan University, Toronto, ON, Canada-M5B 2K3
[2]Dr Robot Inc., 44 East Beaver Creek Rd, Suite 8, Richmond Hill, ON, Canada-L4B 1G8

Abstract**—***The paper presents a comprehensive analysis of recent advancements in autonomous lunar exploration technologies, with a particular emphasis on the development of a Force Sensing Gripper for robotic manipulation in complex, unpredictable space environments. We trace the evolution of lunar exploration, from early missions to modern multi-rover systems with enhanced autonomy, focusing on the technological innovations that overcome the Moon's challenging terrain. Central to this exploration is the Lunar Exploration Rover System (LERS), a cutting-edge platform designed for both navigation and task execution on the lunar surface. A key component of LERS is an intelligent, force-sensitive gripper designed for precise manipulation in low-gravity conditions. This two-fingered gripper, equipped with force-sensitive resistors (FSRs), provides real-time feedback on force dynamics, enabling safe and accurate handling of various objects in the Moon's microgravity. The gripper's modular design integrates a 5-turn speed servo for linear control and torque-based servos for wrist rotation and gripping functions, all coordinated by an ESP32 microcontroller that processes sensor data to optimize performance in real time. The deep learning framework enhances this system's adaptability, ensuring robust performance in space's extreme conditions. The innovations discussed here not only advance space robotics but also offer significant potential for terrestrial industries requiring precise, adaptive robotic systems in challenging environments. This work addresses key limitations in current gripper technologies, representing a transformative step in the development of versatile robotic systems capable of supporting future lunar missions and beyond.*

Keywords**—** *Intelligent Grippers, Design of Lunar Rovers, Multi-Rover Robotics, Modular Design .*

I. INTRODUCTION

Space exploration has evolved from an era of speculation to a robust scientific endeavor, with the Moon serving as a key destination. Lunar Exploration Rover Systems (LERS) play a pivotal role in this journey, aiming to support both scientific discovery and the development of technologies for future space missions.

Navigating the Moon's rugged terrain presents a host of challenges, from navigating uneven surfaces to dealing with extreme temperature fluctuations. As a result, lunar rovers must be designed for versatility, endurance, and mobility. Early lunar exploration efforts—such as the USSR's Lunokhod and NASA's Apollo missions—established a foundation, but modern systems now prioritize autonomy, mobility, and operational reliability [1-3].

Exploration platforms, whether stationary or mobile, must accommodate the Moon's complex geological and mineralogical diversity. In contrast to stationary systems, mobile rovers are uniquely suited to cover vast distances (up to 500 kilometers), conduct geological sampling, and perform on-site scientific analysis [3]. Recent advancements have improved rovers' capabilities, allowing them to traverse the lunar landscape more efficiently and access remote or challenging areas.

Technological improvements in lunar rover design have focused on enhancing both mechanical and autonomous systems. Rovers like NASA's Curiosity and ESA's ExoMars have made significant strides in autonomy, mobility, and environmental resilience, demonstrating the importance of evolving movement systems and self-governing control for space exploration [4-7]. Studies on rover dynamics, particularly in sandy or granular terrains, continue to contribute valuable insights into vehicle-terrain interactions, with works like those by Irani and Bauer providing a foundational understanding of how rovers perform on extraterrestrial surfaces [8-10].

Moreover, contemporary research on adaptive wheel designs and the integration of suspension systems, such as the rocker-bogie mechanism, has led to more effective navigation strategies [11-16]. These advancements allow rovers to handle the Moon's diverse and unpredictable terrain while conserving energy and maintaining stability. Recent research into wheeled locomotion mechanics and multi-rover systems also highlights the increasing complexity of lunar exploration, including the coordination of multiple autonomous units across vast lunar regions [17,18].

Though lunar rovers have evolved, they continue to face challenges related to energy management, obstacle negotiation, and environmental adaptability. Studies in rover mobility dynamics and autonomous control systems, such as the work by Kalaycioglu and De Ruiter, have significantly advanced understanding in this field, laying the groundwork for future innovations in multi-rover systems and coordinated operations [19-26].

As lunar exploration technologies advance, the focus has expanded from mobility to precision manipulation, which is essential for tasks like assembling infrastructure, managing space debris, and conducting detailed scientific experiments. Robotic grippers have seen substantial innovation in recent years, becoming indispensable for handling objects in unstructured and unpredictable environments like space.

Historically, robotic grippers were rigid and lacked the dexterity necessary for intricate manipulation tasks. Early designs, while sufficient for specific functions, often struggled with adaptability when encountering irregular or fragile objects. The development of compliant and soft robotic grippers marked a significant evolution, enabling safer and more flexible object handling, especially in space environments where variability in object shapes and sizes is common [27].

Traditional rigid grippers, while effective for specific tasks, often lack the dexterity and adaptability required for applications involving delicate or irregularly shaped objects. Early designs, such as vacuum, pneumatic, hydraulic, and servo-electric grippers, provided foundational capabilities but were often limited in their application to specific tasks or objects of fixed sizes and shapes [28]. The development of robotic hands has seen significant progress over the past century, as detailed in [29].

Soft robotics has emerged as a crucial field in the design of grippers, offering the ability to deform and conform to objects, thus expanding the scope of applications. Research by Averta et al. (2021) and others has underscored the importance of biologically inspired designs that mimic the adaptability of the human hand for space applications, allowing robots to operate effectively in complex, unstructured environments [30]. These grippers are typically made from flexible materials such as silicone, elastomers, or thermoplastic polyurethane (TPU), which allow for safe interaction with delicate objects [31,32]. However, challenges remain in achieving consistent and reliable performance across varying object sizes, shapes, and textures. Traditional soft grippers often lack the robustness and control precision required for complex tasks, especially in hazardous or unstructured environments such as space exploration.

Adaptive gripping mechanisms, such as those employing under actuation and differential mechanisms, have been explored to overcome these challenges. Birglen and Gosselin (2006) investigated the force analysis of connected differential mechanisms for grasping applications [33]. Similarly, Hirose and Umetani (1978) developed soft grippers for versatile robot hands, laying the groundwork for future advancements in adaptive gripping [34].

The integration of novel materials and actuation technologies has further enhanced the versatility of soft grippers. Materials such as dielectric elastomers, ionic polymer-metal composites (IPMC), and shape memory alloys (SMA) have expanded the potential applications of soft grippers in fields like biomedical surgery, space exploration, and industrial automation [35].

One approach to overcoming the limitations of traditional soft grippers is the integration of compressible materials within the gripper design. Thermoplastic polyurethane (TPU) has emerged as a particularly promising material due to its flexibility, durability, and resistance to deformation under load [36]. TPU's compressibility provides grippers with the capability to adjust to different object dimensions and textures without requiring multiple actuators or complex control systems [37].

The use of Shape Memory Alloys (SMAs) in actuators for compliant grippers represents another significant advancement. SMAs have the unique ability to remember their original shape after deformation and revert to it when exposed to certain stimuli, typically heat. This property has made them highly attractive for use in robotic systems that require adaptive and responsive actuation mechanisms. SMA springs, in particular, have demonstrated superior energy density, strain capability, and flexibility, making them ideal for applications requiring significant adaptability and range of motion [38-40]

Boyd and Lagoudas (1996) provided a thermodynamic constitutive model for shape memory materials, contributing to the understanding and application of these smart materials in robotic grippers [41]. The development of reconfigurable compliant grippers using SMA springs has opened new possibilities in robotic manipulation, enabling the handling of objects with varying shapes and sizes [42].

The development of universal grippers capable of adapting to diverse tasks without requiring complex reconfiguration has also garnered significant attention. Technologies such as granular jamming enable grippers to conform to the shape of an object by applying pressure and locking in place, allowing for the secure handling of both soft and hard materials [43-45]. These advancements build upon earlier work in robotic grasping and manipulation, such as that of [46-48].

The integration of vacuum systems and soft robotic materials into gripper designs has further enhanced their capabilities. The combination of vacuum systems with soft materials enables grippers to handle delicate objects without causing damage, a crucial requirement in industries like electronics manufacturing and potentially in space-based manufacturing [49].

Innovative approaches to gripper design have also drawn inspiration from biological systems. The work of Deimel and Brock (2016) on compliant hands based on novel pneumatic actuators represents a significant step in this direction [50]. Similarly, the development of adaptive robotic grippers, as described by Ansary et al. (2023), showcases the potential for creating more versatile and efficient gripping systems [51,52].

The creation of modular and detachable soft robotic grippers with tactile feedback, as explored by Iqbal et al. (2019), offers promising solutions for human-robot collaboration in space environments [53,54]. Additionally, the development of underactuated soft robotic grippers for high-speed object grasping and manipulation, as demonstrated by Kakogawa et al. (2018), addresses the need for rapid and reliable object handling in dynamic space scenarios [55,56].

Other actuation systems, such as tendon-driven and magnetic actuation mechanisms, offer alternative approaches for operating grippers in space. However, TDMs introduce complexity into the kinematics and statics of the system, particularly when accounting for the non-linear relationships between tendon extension and joint angles Tendon-driven designs transmit forces using inelastic tendons, reducing system weight, while magnetic actuation offers the potential for fine manipulation in microgravity without direct contact [57-58]. These systems are particularly valuable for reducing mechanical complexity while maintaining high functionality in space.

The key advantage of tendon-driven systems is their ability to transmit forces through smaller actuators, which reduces the size and weight of the overall system. However, they present a challenge in controlling the torque at the joints, especially when the tendons are elastic, which can complicate the kinematics of the system. Gosselin and Laliberté (2008) provided a comprehensive analysis of force transmission and design considerations for tendon-driven robotic hands [57].

Magnetic actuation, on the other hand, offers an innovative approach for space missions. Magnetic-controlled grippers allow for fine manipulation of objects without requiring direct physical connection to an actuator, which can simplify design and reduce potential points of failure in a robotic system. This technology is particularly suited for space missions where traditional motors and actuators may struggle due to environmental constraints such as microgravity or vacuum conditions [60-61].

The development of magnetic helical miniature robots with soft magnetic-controlled grippers represents a significant advancement in this field. These systems demonstrate efficient propulsion in low Reynolds number environments, making them ideal for biomedical operations and potentially adaptable for space applications [62, 63] The work of Berg and Anderson (1973) on bacterial flagellar motion has provided inspiration for some of these designs [64].

The use of robotic grippers in space is a growing area of interest, particularly for tasks such as debris removal, satellite servicing, and in-space manufacturing. The harsh conditions of space, including microgravity, extreme temperature variations, and the absence of direct human intervention, necessitate grippers that can autonomously adapt to various object geometries while providing reliable feedback on their interactions [65].

Recent research has focused on developing innovative gripper designs that address the unique challenges of space applications. For instance, the TriTrap gripper, inspired by insect tarsal chains, utilizes a series of linked segments actuated by a single tendon. This biomimetic design demonstrates how nature-inspired solutions can lead to simple yet effective manipulation strategies for space applications [66,67].

Topology optimization (TO) has emerged as a powerful tool for creating lightweight yet robust gripper structures suitable for space applications. Monteiro et al. (2024) demonstrate the use of TO in designing a robotic gripper made from stainless steel, achieving substantial weight reduction while maintaining structural integrity [64]. This approach, combined with additive manufacturing techniques, offers new possibilities for creating grippers tailored to the specific requirements of space missions [69-71].

Recent advancements in soft robotics have led to the development of compliant grippers that can conform to irregular shapes without causing damage to delicate components [72]. These soft end-effectors, inspired by biological systems such as the octopus's arms, offer superior adaptability in unstructured environments [73].

The development of latching mechanisms for end-effectors has evolved in parallel with advancements in space technologies. Multifunctional coupling interfaces like HOTDOCK are designed to provide robust and secure connections between space systems, ensuring that end-effectors can perform tasks such as docking, tool changing, and payload handling with minimal human oversight [74].

The incorporation of artificial intelligence into robotic agents represents a major leap forward in terms of adaptability and accuracy. AI-driven systems allow grippers to learn from their environment and make real-time adjustments based on sensory input, a capability that is particularly valuable in space, where environmental conditions are often unpredictable.

Learning-based methods, including vision-based machine learning, have emerged as promising alternatives to traditional analytic models. These methods enable robots to perform tasks such as object localization, pose estimation, and grasp planning, even when dealing with unfamiliar objects or intricate spatial arrangements. Vision-based machine learning allows for continuous learning and adaptation, which is essential for performing dexterous manipulation in cluttered or dynamic environments [75,76].

The use of force-sensitive resistors (FSRs) in grippers allows robots to perceive and respond to the forces they encounter. This capability can prevent damage to both the gripper and the object being manipulated, which is critical during delicate operations such as spacecraft docking or in-space manufacturing. By leveraging AI, robotic grippers can improve their ability to grasp and manipulate objects of varying sizes, weights, and materials. The tactile feedback from sensors such as FSRs is processed by AI algorithms, which then adjust the gripper's actions in real-time to optimize performance [77].

Advancements in sensor technologies have also significantly improved the capabilities of end-effectors in dexterous manipulation tasks. For example, the integration of optomechanical touch sensors into smart end speakers has increased their ability to control weak objects with high precision [78]. These developments align with the growing trend of creating "smart" end-effectors capable of autonomous operation in space and other challenging environments [79].

The work of Ronneberg et al. (2020) on revealing relationships between porosity, microstructure, and mechanical properties of laser powder bed fusion materials could inform the development of more durable and efficient gripper structures for space applications [80]. Similarly, the research of Sugavaneswaran et al. (2020) on the design of robot grippers with topology optimization and additive manufacturing techniques offers promising avenues for creating customized, lightweight grippers for specific space missions [81].

Despite significant advancements, several challenges remain in the development of robotic grippers for space applications. These include:

- Long-term durability of soft materials and smart actuators in the harsh space environment.
- Integration of robust force and moment feedback systems that can operate reliably in microgravity.
- Development of control algorithms that can adapt to the unique dynamics of object manipulation in microgravity.

- Enhancement of AI and machine learning systems to handle unpredictable scenarios in space operations.
- Optimization of power consumption and efficiency for limited energy resources in space missions.
- Improvement of reliability and redundancy in gripper systems to ensure mission success without direct human intervention.
- Investigation of long-term effects of space conditions on advanced sensors and actuators.

The integration of advanced robotic gripper systems with deep learning and adaptive materials presents significant potential for both lunar exploration and broader space applications. By addressing the limitations of current gripper technologies, such as the lack of force feedback and adaptability in microgravity, this research paves the way for more versatile and reliable robotic systems. As space exploration continues to evolve, the development of intelligent robotic systems will play a critical role in ensuring the success of future missions, from lunar bases to interplanetary travel.

The remainder of this paper is organized as follows: Section 2 discusses the operational capabilities of the Lunar Exploration Rover System (LERS) and outlines its mission objectives. Section 3 delves into the system architecture of LERS, highlighting the key components that enable its autonomous functionality. In Section 4, we focus on the design and development of the Force Sensing Gripper, detailing its mechanical design and features. Finally, Section 5 offers concluding remarks and insights into future work.

II. LERS MISSION OBJECTIVES AND OPERATIONAL CAPABILITIES

The Lunar Exploration Rover System (LERS) represents a pivotal advancement in lunar exploration, offering a broad spectrum of capabilities to support a wide array of missions (Fig. 1a). With its versatile design, LERS is capable of performing tasks that enhance both robotic and human-led missions, pushing the boundaries of what is possible on the lunar surface.

One of the primary missions of LERS is scientific exploration and terrain mapping, where the rover navigates across diverse lunar landscapes to generate high-resolution topographical maps. These maps are essential for planning future exploration routes and identifying scientifically significant locations. By autonomously charting the lunar surface, LERS plays a crucial role in understanding the Moon's geological history and identifying potential resource-rich areas.

Sample acquisition and analysis is another core function of LERS, where it utilizes its robotic arm to collect rock and soil samples from various lunar regions. The detailed analysis of these samples offers insights into the Moon's formation, evolution, and potential for supporting future human settlements. Through subsurface drilling and routine collection of regolith, LERS provides critical data on the composition and resource potential of the Moon.

In addition to these scientific missions, LERS plays a vital role in construction and infrastructure development. The rover’s robotic arm is specifically designed to assist with erecting structures, deploying instruments, and performing maintenance on lunar habitats and other installations. These capabilities are essential for establishing a long-term human presence on the Moon, including setting up outposts and assembling key infrastructure components.

Fig. 1a. LERS Mission Objectives and Operational Capabilities

LERS also supports autonomous operations, where it performs exploratory tasks independently, such as assessing geological formations, locating water ice deposits, and identifying mineral resources. Its autonomy allows for continuous exploration, even when human operators are unavailable, ensuring that valuable data is collected over extended periods.

Further, LERS is equipped for remote sensing and control, which allows mission operators on Earth to precisely guide the rover's activities in real-time. This capability is critical for conducting delicate tasks in difficult-to-reach areas, enabling accurate deployment of scientific equipment and ensuring the safety of lunar operations.

Additionally, LERS can be integrated into international collaborative missions, supporting shared exploration goals with other space agencies. Its ability to transport equipment, deploy instruments, and carry out cooperative tasks enhances global efforts to explore the Moon and develop sustainable lunar operations.

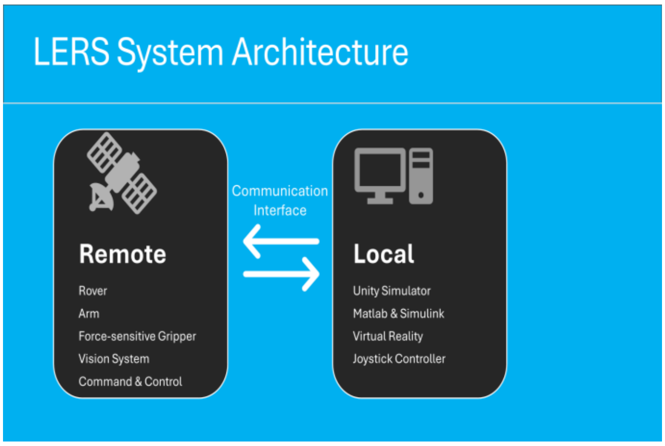
A key feature of LERS is its force-sensitive gripper, which significantly enhances its ability to perform critical tasks on the lunar surface. This sophisticated gripper, integrated with force-sensitive resistors (FSRs), enables precise manipulation of objects in the Moon's low-gravity environment. Through real-time feedback on force direction and magnitude, the gripper ensures safe handling of delicate instruments and irregularly shaped objects, making it ideal for routine scientific investigations such as gravimetry, magnetometry, and spectrometry. The gripper’s fine-tuned control also plays a crucial role in resource exploitation, allowing for accurate extraction of valuable materials like water ice and minerals, essential for sustaining long-term lunar missions. Furthermore, the gripper enhances LERS' logistical capabilities, enabling the efficient transportation of scientific samples and equipment between different lunar sites and transport vehicles, thus supporting both autonomous and collaborative missions

III. LERS SYSTEM ARCHITECTURE OVERVIEW

The Lunar Exploration Rover System (LERS) is designed as a versatile platform to support a wide range of lunar missions, with its architecture specifically tailored to meet the demands of lunar exploration. The system architecture is a carefully structured combination of various subsystems, each playing a crucial role in ensuring the rover's operational efficiency and reliability. At its core, LERS integrates both autonomous remote and local subsystems, which communicate seamlessly via a sophisticated communication interface, enabling smooth coordination between the rover's exploratory functions and the robotic arm's manipulation capabilities.

The overall architecture of LERS is divided into two main components: the remote subsystem and the local sub-system (Fig. 1b). These systems are connected through a central control unit that manages data flow and decision-making processes. The remote subsystem is responsible for navigating the rugged lunar terrain, relying on advanced sensors, cameras, and real-time navigation algorithms to ensure smooth traversal. This subsystem also includes the force-sensitive gripper, and is designed for precise interaction with the environment, capable of handling delicate objects and conducting detailed scientific tasks. The local subsystem encompasses Unity Simulator, Virtual Reality Tools and MATLAB/Simulink simulation environment as well as the Hand-controllers (Fig. 1c).

Each subsystem is linked through a robust communication network that facilitates real-time data exchange between the rover and mission control on Earth. This ensures that LERS can operate both autonomously and under human supervision subject to time delays when necessary. The architecture is built around a modular design approach, allowing for future upgrades and the integration of additional tools or sensors as mission requirements evolve.


LERS System Architecture

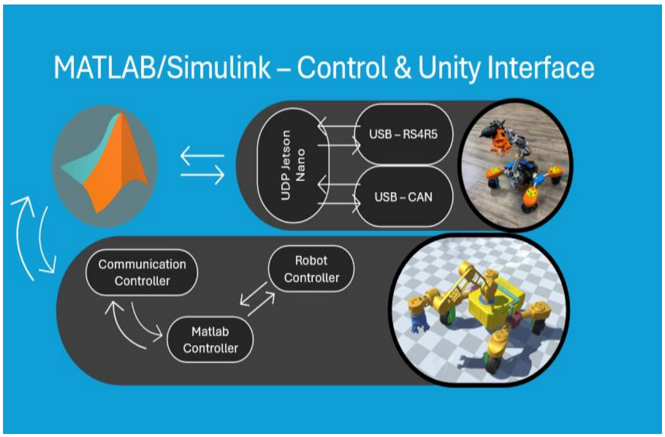
Remote
Rover
Arm
Force-sensitive Gripper
Vision System
Command & Control

Communication Interface

Local
Unity Simulator
Matlab & Simulink
Virtual Reality
Joystick Controller

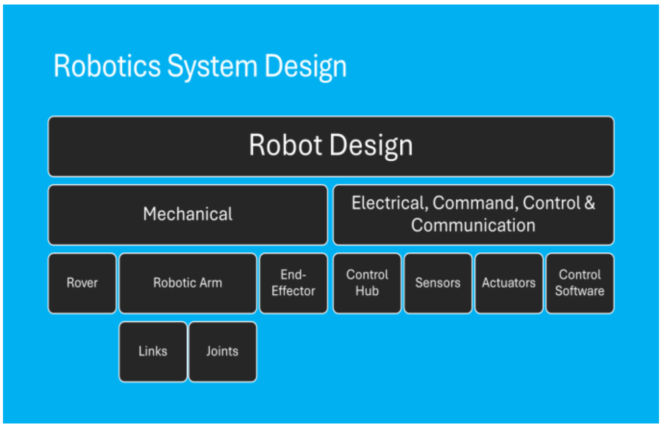
Fig. 1b. LERS High-Level System Architecture

The development of LERS followed a structured, iterative design process, with each stage focused on optimizing both mechanical performance and software functionality (Figs. 2-3). Detailed simulations and physical testing were conducted to ensure that the rover and its robotic arm could meet the challenging conditions of the lunar environment, from navigating steep slopes to precisely manipulating objects in low-gravity conditions. The testbed configuration, representing a real-world lunar scenario, was critical in refining the system architecture, validating the robustness of the design, and ensuring that all subsystems work harmoniously to achieve the mission objectives.


MATLAB/Simulink – Control & Unity Interface

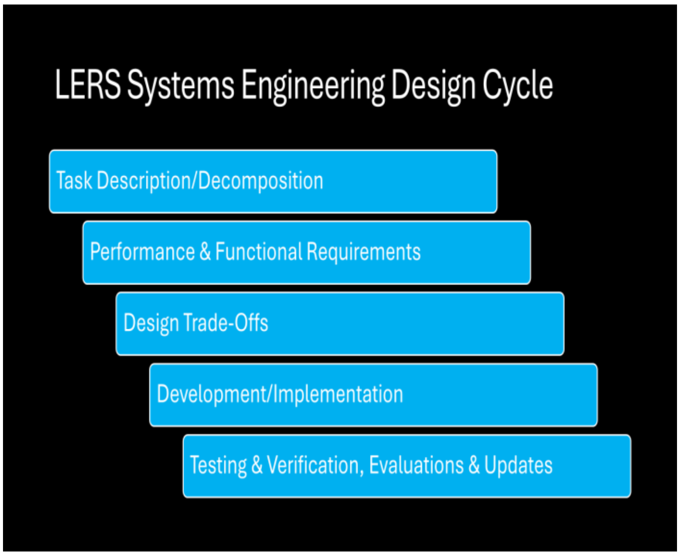
UDP Jetson Nano
USB – RS4R5
USB – CAN
Communication Controller
Robot Controller
Matlab Controller

Fig. 1c. MATLAB/Simulink^{TM} – Control and Unity Interfaces


Robotics System Design

Robot Design
Mechanical
Electrical, Command, Control & Communication
Rover
Robotic Arm
End-Effector
Control Hub
Sensors
Actuators
Control Software
Links
Joints

Fig. 2. LERS Physical System Design Diagram


LERS Systems Engineering Design Cycle

Task Description/Decomposition
Performance & Functional Requirements
Design Trade-Offs
Development/Implementation
Testing & Verification, Evaluations & Updates

Fig. 3. Process of LERS Systems Engineering Design Cycle

IV. FORCE-SENSITIVE GRIPPER DESIGN

The force-sensitive gripper in the Lunar Exploration Rover System (LERS) is a robust, adaptable component designed to handle delicate and varied objects in challenging environments, such as the lunar surface.

The system is based on a compliant two-finger configuration, allowing for precise manipulation of objects while maintaining the necessary flexibility and durability required in space operations. Central to the gripper's effectiveness is its force-sensing capability, made possible through force-sensitive resistors (FSRs) integrated into each finger. These sensors provide real-time feedback on the forces applied during gripping, ensuring careful handling of sensitive materials.

Each finger is equipped with two FSRs connected through a 100K Ohm resistor, which allows for highly sensitive and accurate force readings. The FSRs detect the pressure applied during gripping, providing data that the system uses to adjust grip strength in real time. This real-time feedback is crucial for safely interacting with objects of varying fragility, such as lunar rocks or scientific instruments. The FSRs, along with the servo motors that control finger movement, are all connected to an ESP32 Dev Module via an ESP32 Shield, creating a reliable and responsive control system. The ESP32 serves as the brain of the gripper, processing sensor data and sending commands to the servos to adjust the grip accordingly.

The fingers themselves are 3D printed using thermoplastic polyurethane (TPU), a material chosen for its unique combination of flexibility and strength. TPU allows the fingers to bend and conform to the shape of objects, providing a soft but firm grip. This flexibility is essential for handling delicate items without applying excessive force, while the durability of TPU ensures the fingers can withstand the rigors of repeated use in harsh lunar conditions. The design of the fingers features V-shaped teeth and valleys, which allow the fingers to bend naturally and grip objects more effectively. A central hole runs through each finger, allowing a control string to pass through. This string is tied to a locknut at the end, which enables precise control over finger movement.

The movement of the fingers is controlled by a pulley system driven by a servo motor. The pulley system converts the rotary motion of the servo into linear motion to adjust the position of the fingers. As the servo rotates the pulley, it pulls or releases the string connected to both fingers, causing them to extend or contract. This design allows for smooth, precise control of the gripper’s movement, ensuring that it can adjust its grip based on the size and shape of the object it is handling. The pulley and housing are both 3D printed using polylactic acid (PLA), a strong, rigid material that provides structural integrity to the system Fig. 4 shows the CAD model of the gripper. The pulley itself is designed with five holes to route the strings controlling each finger, and it includes slots to prevent the strings from tangling with each other.

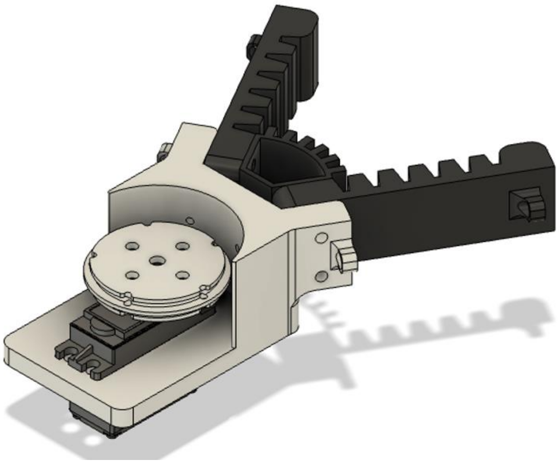


Fig. 4. CAD model of Gripper

The finger design also incorporates structural enhancements to improve its performance. The last valley of each finger is thickened to ensure that the lower sections of the finger curve first, enhancing the contact area between the FSRs and the object being gripped. This function improves the accuracy of the force reading and ensures that the fork is evenly distributed over the entire object. Additionally, the angled flat surface on the fingertip allows for easy mounting of the FSRs, ensuring that they remain securely attached during operation. A small hole on the side of each finger is included to accommodate surgical tubing, which acts as a return mechanism. This tubing functions like a rubber band, pulling the finger back to its original position after it has been extended. The use of surgical tubing prevents the fingers from suffering plastic deformation, which could occur if the fingers were repeatedly stretched without a return mechanism. The bridge between the fingers provides additional support, ensuring a firm grip on objects (see Fig. 5a and 5b).

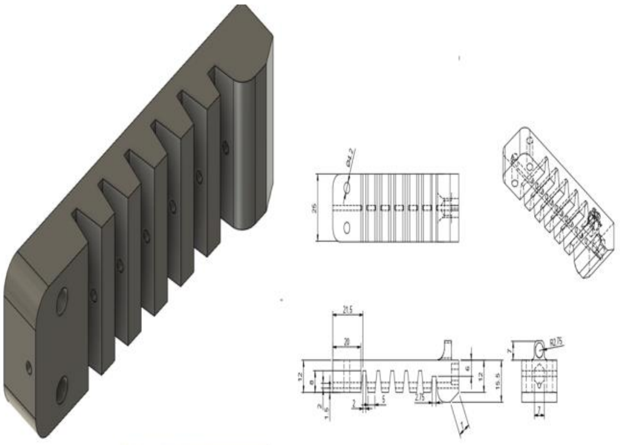


Fig. 5a. CAD model of Fingers

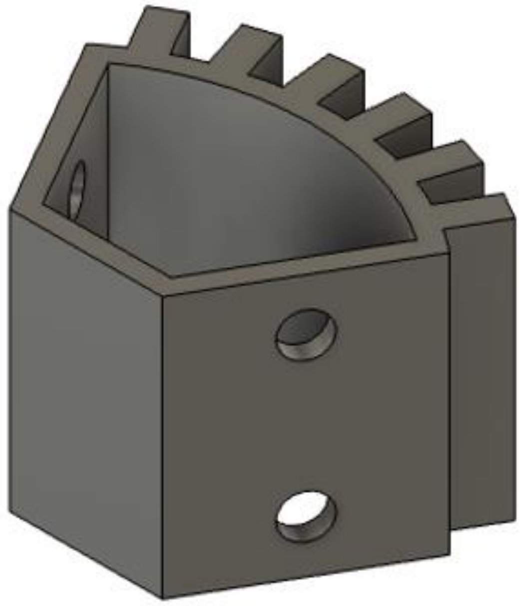


Fig. 5b. CAD model of the Middle Structure

The housing structure for the gripper plays a crucial role in supporting the servo and guiding the movement of the fingers. The housing is equipped with a mount for the servo that drives the pulley system, and it includes two central holes through which the control strings pass. These strings are connected to the fingers, and their movement is controlled by the rotation of the pulley. The housing also includes two side mounts for securely attaching the fingers, ensuring that they remain stable during operation. An additional hole on the housing allows the surgical tubing to pass through, maintaining the tension required to return the fingers to their neutral position (Fig. 6 shows the housing structure).

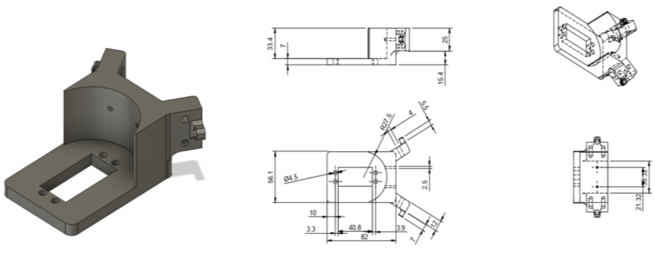


Fig. 6. CAD model of the Housing Structure

The pulley mechanism itself is designed with precision and functionality in mind. It includes multiple holes through which the control strings are routed, ensuring that each finger moves in sync with the other. This single-strand control system ensures that the tension on both fingers is always equal, preventing uneven movement that could lead to ineffective gripping. The pulley is securely attached to the servo via four mounting holes, providing a stable platform for precise control over the gripper's movements Fig. 7a and b shows the pulley structure.

Fig.7a. CAD model of the Pulley Structure

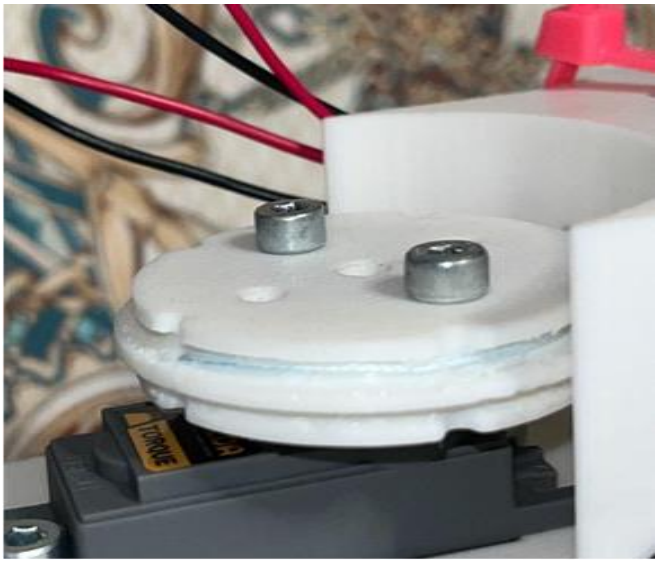


Fig.7b. The Pulley Structure Prototype

The gripper's overall functionality is enhanced by the combination of flexible TPU fingers, force-sensitive resistors, and the precise control provided by the servo-driven pulley system. This design allows the gripper to handle a wide range of objects, from delicate scientific instruments to irregularly shaped lunar samples, with a high degree of precision and care. The inclusion of force feedback through the FSRs ensures that the system can dynamically adjust its grip strength to prevent damage to fragile objects, while the TPU material and structural features of the fingers allow for a firm but flexible grip. The integration of the surgical tubing return mechanism prevents long-term wear and deformation of the fingers, ensuring the gripper's durability over extended use in harsh environments.

Figure 8a-e presents the fully integrated gripper prototype, showcasing the complete assembly and detailed CAD models. These include close-up views of the finger with the embedded force sensors, highlighting the precision in sensor placement, as well as the pulley mechanism, which illustrates the string-driven control system. The figures provide a comprehensive overview of the design, emphasizing both the structural components and the functional integration of the force-sensitive elements.

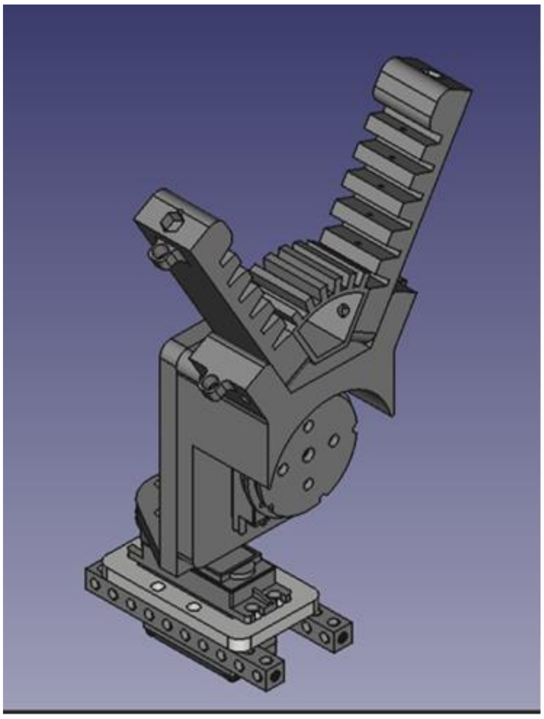


Fig. 8a. CAD Model of the Gripper Assembly

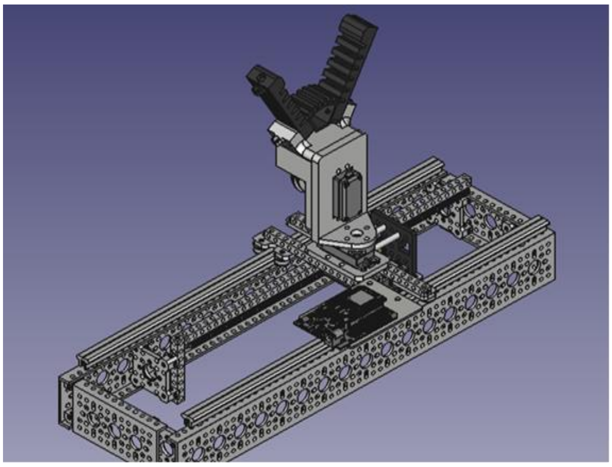


Fig. 8b. Integrated Gripper CAD model

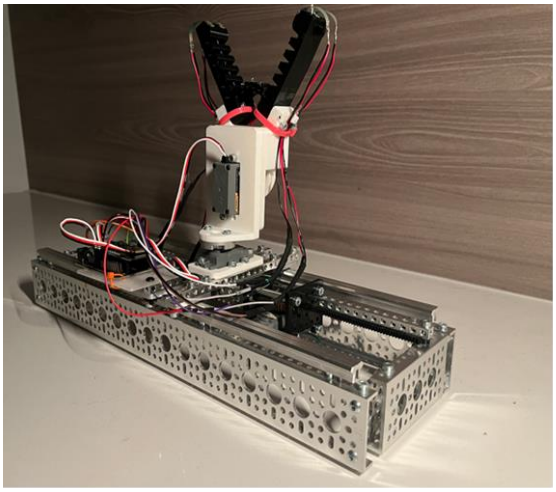


Fig. 8c. Integrated Gripper with Force Sensors

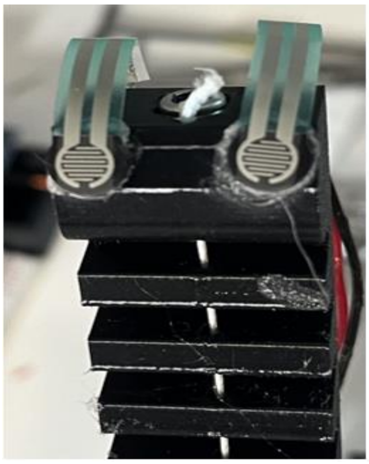


Fig. 8d. Integrated Force Sensors with Finger and Pulley Prototype

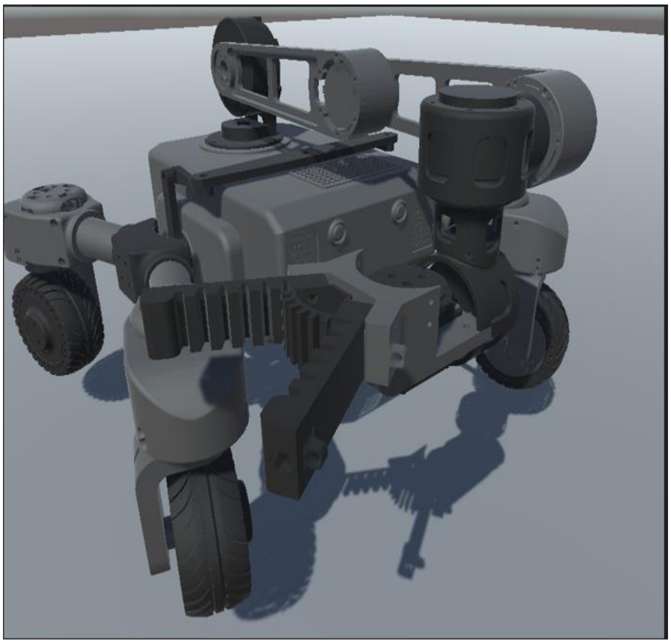


Fig. 8e. Integrated CAD Model for Rover and Robotics Arm with Force Sensors with Finger

The electrical and electronics components of the force-sensitive gripper are centered around the highly efficient ESP32 microcontroller, which acts as the primary hub for processing sensor data and controlling the gripper's actuation. The gripper is equipped with force-sensitive resistors (FSRs) that provide real-time feedback on the forces applied during object manipulation. These FSRs are connected to the ESP32 via 100K Ohm resistors to ensure high accuracy and sensitivity in force measurements. The dual-mode servos, used for both prismatic and revolute joints, deliver precise torque-based control for the gripper’s wrist and finger movements. These servos allow for fine adjustments in both linear and rotational motions, critical for handling fragile or irregularly shaped objects. Communication between the gripper and the control system is handled by the ESP32's integrated Wi-Fi and Bluetooth modules, which transmit sensor data and receive commands via a web server built using the SPIFFS file system. The entire system is programmed using Platform IO, built on the Arduino platform, allowing for flexible programming and rapid development cycles. Fig. 9 illustrates the data acquisition process from the FSRs, providing a visual overview of how sensor readings are captured and transmitted to the control system.

The force-sensitive gripper integrates mechanical, electrical, and control subsystems into a cohesive system capable of performing complex manipulation tasks in challenging environments. The FSRs provide critical feedback to the ESP32 microcontroller, which processes the data to control the servos in real time. This allows the gripper to autonomously adjust its grip force, making it highly adaptable to the varying characteristics of the objects it encounters, such as shape, size, and fragility. The use of 3D-printed TPU for the gripper fingers enhances both durability and flexibility, allowing the system to handle delicate or irregular objects without damaging them. The GoBilda$^{\text{TM}}$ servos, known for their high torque and precision, enable accurate control of both linear and rotational movements, making the gripper versatile enough for a wide range of applications, from space operations to terrestrial robotics .

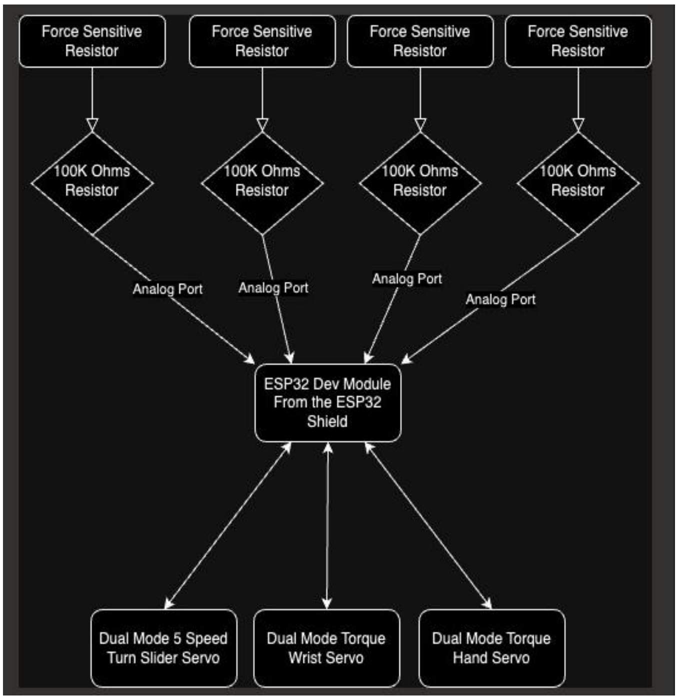


Fig. 9. Data acquisition Process for the Gripper Sensors

Extensive testing of the gripper system was conducted using objects of varying sizes, weights, and materials to evaluate its performance in real-world scenarios. The force-sensitive data collected during these tests demonstrate the system’s ability to consistently apply the correct amount of force for each object, dynamically adjusting in response to changes in the object’s characteristics. The experimental results confirmed the gripper’s capability to handle complex manipulation tasks with precision, even in unstructured and unpredictable environments, such as those encountered in space exploration.

V. CONCLUSION

In conclusion, the Lunar Exploration and Robotic System (LERS) marks a substantial advancement in space exploration technology, particularly for lunar operations. By integrating the rover's mobility with the precision offered by robotic arms, LERS is well-equipped to handle the diverse challenges posed by the Moon’s harsh and uneven terrain. Each element of the system, from its movement mechanisms to the intricate design of its robotic arms, has been carefully engineered to meet the unique demands of lunar missions.

The development process is further enhanced by the use of a comprehensive testbed system, which provides a framework for systematically evaluating and improving LERS's performance. Through detailed simulations and an interactive control platform, the system can be rigorously tested in a controlled environment before deployment, ensuring that all functionalities are validated in simulated lunar conditions.

The force-sensitive gripper developed in this research integrates cutting-edge sensing, actuation, and control technologies for precise handling in difficult environments. With the use of force-sensitive resistors, a modular design, and real-time sensor feedback, the system offers exceptional dexterity and flexibility. These features make it suitable for a variety of applications, such as satellite maintenance, debris handling, and in-space assembly operations.

However, it is important to recognize that this prototype remains in the developmental phase. While LERS exhibits significant potential, further testing and refinement are necessary. The current system iteration requires enhanced control algorithms to guarantee reliable performance across different lunar terrains. Continued calibration and hardware validation will be critical as we move forward. In future research, we aim to integrate more advanced control techniques, ensuring the practical application of these technologies in the lunar rover's operational deployment.

REFERENCES

[1] Siddiqi AA. Beyond Earth: a chronicle of deep space exploration, 1958–2016 (PDF), The NASA history series. second ed. Washington, DC: NASA History Program Office; 2018. p. 1. ISBN 9781626830424. LCCN 2017059404. SP2018–4041
[2] G. G. Raykunav, “Fundamental Space Research”, Fismatlit, ISBN: 978-5-9221-1559-9, Moscow, p. 457, 2014..
[3] E.N. Slyuta, A.V. Vasilev and I. Y. Dalyaev, “Robot-Geologist”: scientific tasks and technical configuration,” in *Proceedings of 48th Lunar and Planetary Science Conference*, March 20-24, 2017.
[4] D.E. Wilhelms, “The Geologic history of the moon”, United States Government Printing Office, ISBN: 1495919854, Washington, p. 329.
[5] J. Wilson, “How we’ll get back to the moon”, *GoddardView*, vol. 1, no. 2 2 3, 2005.
[6] P. Putz, “Space robotics in Europe: A survey”, *Robot. Auton. Syst*., 23, 3–16, 1998.
[7] R., Siegwart, P. Lamon, T. Estier, M. Lauria, and R. Piguet, “ Innovative design for wheeled locomotion in rough terrain”, *Robot. Auton. Syst.*, vol. 40,pp. 151–162, 2002.
[8] R. Irani, R. Bauer, R. and A. Warkentin,. “A dynamic terramechanic model for small lightweight vehicles with rigid wheels and grousers operating in sandy soil” *J. Terramech.* vol. 48, p. 307–318, 2011.
[9] I. KojiroIizuka, L. Kubota, M. Takashi, 2009. “Study of flexible wheels for lunar exploration rovers: running performance of flexible wheels and various amount of deflection”, *J. Asian Electric Veh*. 7 (2), 2009.
[10] I. KojiroIizuka, K., Yasuharu, M. Takashi, 2008. “Study on Wheeled forms of lunar robots for traversing soft terrain”. In: 2008 *IEEE/RSJ*

International Conference on Intelligent Robots and Systems, Acropolis Convention Center, Nice, France, September 22– 26, 2008.

[11] N. Patel, R. Slade, C. Richard, J. Clemmet, 2010. The Exomars rover locomotion subsystem. J. Terramech. Vol. 47,p. 227–242. 2010.

[12] A. Torre, F. Della, G., Amalia Ercoli, C. Giancarlo, , 2010. “AMALIA mission lunar rover—the conceptual design of the team ITALIA Rover”, *Acta Astronaut*. 67 vol. (7–8), p. 961–978, 2010.

[13] J. Y. Wong., 2001. Theory of Ground Vehicles, third ed. *John Wiley & Sons Inc.*

[14] J.Y. Wong, 2010. “Terramechanics & Off-Road Vehicle Engineering, Terrain Behavior, Off-Road Vehicle Performance and Design”, second ed., Butterworth-Heinemann, UK., 2010.

[15] F. Barlas, “Design of a Mars Rover suspension mechanism”, M.S. thesis, Izmir Institute of Technology, Izmir, pp 11–18, 2004.

[16] D. Carrier, “Soviet rover systems”, in: *Proceedings of the AIAA Space Programs and Technologies Conference*, 24–27, Huntsville, AL, 1992 Amend, J.R., Brown, E., Rodenberg, N., Jaeger, H.M., and Lipson, H. (2012). A positive pressure universal gripper based on the jamming of granular material. IEEE Transactions on Robotics, 28(2), 341-350.

[17] A. Kemurdjian., V. Gromov, V. Mishkinyuk, V. Kucherenko, and P. Sologub. “Small Marsokhod configuration,” in: *International Conference on Robotics and Automation*, 1, 165–168, IEEE, Nice, France, 1992.

[18] D. Kim, H. Hong, H. Kim, J. Kim, “Optimal design and kinetic analysis of a stair-climbing mobile robot with rocker-bogie mechanism”, *Mechanism and Machine Theory*, Volume 50, 2012, p. 90-108, ISSN 0094-114X, https://doi.org/10.1016/j.mechmachtheory.2011.11.013.

[19] S. Kalaycioglu, A. de Ruiter, “Coordinated Motion and Force Control of Multi-Rover Robotics System with Mecanum Wheels,” in 2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS), IEEE: 1–9, 2022, doi:10.1109/IEMTRONICS55184.2022.9795804.

[20] S. Kalaycioglu, A. de Ruiter, “Nonlinear Model Predictive Control of Rover Robotics System”, *Advances in Science, Technology and Engineering Systems, Journa*l Vol. 8, No. 1, p. 44-56 (2023).

[21] S. Kalaycioglu and De Ruiter A (2023), "Passivity-based Nonlinear Model Predictive Control (PNMPC) of Multi-robot Systems for Space Applications." Frontiers in Robotics and AI, 10:1181128. doi: 10.3389/frobt.2023.1181128.

[22] S, Kalaycioglu, A. de Ruiter, “Dual arm coordination of redundant space manipulators mounted on a spacecraft”, *Robotica*, , pp. 1- 29, https://doi.org/10.1017/S026357472300050, April 2023.

[23] S. Kalaycioglu, S, A. de Ruiter A., L. Jesse, C. Brandon, H. Xie, “Design Concept of Lunar Multi Rover Robotics System (MRSS)”, *International Journal of Scientific and Science (IJSES),* Volume 7, Issue 9, pp 48-54, ISSN: 2456-7361, http://ijses.com/wp-content/uploads/2023/10/71-IJSES-V7N9.pdf, October. 2023.

[24] S. Kalaycioglu, 2021. “Beyond the Final Frontier: Controlling Robotics for Space Use”, *Scientia*. Available at: https://www.scientia.global/dr-sean-kalaycioglu-beyond-the-final-frontier-controlling-robotics-for-space-use/ https://doi.org/ 10.33548/SCIENTIA1078 [Accessed 12 September 2024].

[25] S. Kalaycioglu, A. DeRuiter., Z. Xie, J. Jiang., A. Tseng., H. Xie, . “Lunar Robotics Evolution and Innovative Design - Lecture Notes in Electrical Engineering”, *Springer Nature UK*, 2024. https://link.springer.com/book/9789819747795

[26] S. Kalaycioglu, A. DeRuiter A., Z. Xie, J. Jiang, A. Tseng, H. Xie.. “Lunar Robotics Evolution and Innovative Design” EDAS 2024 *Proceedings of International IoT, Electronics and Mechatronics IEMTRONICS 2024 Conference, IEMTRONICS Conference*, London, UK, April 3-5, 2024, Volume 1, pp. 578-590, | SpringerLink.

[27] D. Rus, and M.T. Tolley, (2015). “Design, Fabrication, and Control of Soft robots”. *Nature*, 521(7553), pp. 467-475.

[28] B. Mason, A. Bicchi, and V. Kumar, "A review of rigid and adaptive robotic grippers," *Proceedings of the Robotic Manipulation Conference*, vol. 5, pp. 89-105, 2000.

[29] P. Piazza, A. Cataldo, and D. Molfese, "Robotic hands: Evolution from rigid designs to soft, compliant systems," *IEEE Transactions on Robotics*, vol. 35, no. 1, pp. 123-135, 2019.

[30] S. Averta, "Biologically inspired soft end-effectors for space applications," *Journal of Robotics and Automation*, vol. 33, pp. 289-301, 2021.

[31] R. Shepherd, R. Morin, and G. Galloway, "Soft robotic grippers for space debris management," *Journal of Soft Robotics*, vol. 12, no. 2, pp. 98-112, 2011.

[32] S. Shintake, E. Schlagenhauf, and S. Rus, "The application of soft robotics in space: Gripper designs for delicate object handling," *Advances in Robotics Research*, vol. 8, no. 3, pp. 211-223, 2018.

[33] L, Birglen, and C.M., Gosselin, (2006). “Force Analysis of Connected Differential Mechanisms: Application to Grasping”. *International Journal of Robotics Research*, 25(10), pp. 1033-1046.

[34] S. Hirose, S. and Y. Umetani, (1978). “The Development of Soft Gripper for the Versatile Robot Hand”. *Mechanism and Machine Theory*, 13(3), pp. 351-359.

[35] H. Kim, T. Shibata, and M. Takeuchi, "Novel materials in soft robotics: Applications in space grippers," *Materials Science & Engineering Journal*, vol. 17, pp. 82-94, 2019.

[36] S, Kim, S., C, Laschi, and B., Trimmer, (2019). “Soft robotics: A bioinspired evolution in robotics”. *Trends in Biotechnology*, 31(5), 287-294.

[37] J. Hughes, S. Jiang, and D. Robertson, "Exploring thermoplastic polyurethane (TPU) in soft robotic designs," *Journal of Advanced Robotics*, vol. 20, no. 2, pp. 145-163, 2020.

[38] T. Seelecke and H. Muller, "Shape memory alloys in robotic actuation systems," *Journal of Intelligent Systems*, vol. 14, pp. 123-138, 2012.

[39] S. J., Furst, and S. Seelecke, (2012). “Modeling and experimental characterization of the stress, strain, and resistance of shape memory alloy actuator wires with controlled power input”. *Journal of Intelligent Material Systems and Structures,* 23(11), pp.1233-1247.

[40] L. Chen, Y. Zhou, and F. Zheng, "Reconfigurable compliant grippers with shape memory alloy actuation," *Journal of Robotic Systems*, vol. 45, no. 1, pp. 99-112, 2024.

[41] R. Boyd and D. Lagoudas, "Constitutive models for shape memory materials in grippers," *International Journal of Mechanics*, vol. 17, no. 1, pp. 45-62, 1996.

[42] W., Chen, and W. Lin (2013). “Design and analysis of flexure-based soft grippers for delicate manipulation”. *Journal of Mechanisms and Robotics*, 5(4), 041007.

[43] W. Chen, W. Lin, and Y. Zhang, "Soft robotic grippers with sensing capabilities: A review," *Journal of Intelligent Material Systems and Structures*, vol. 31, no. 4, pp. 447-462, 2020.

[44] E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz., M.R. Zakin, H. Lipson, and H.M. Jaeger, (2010).” Universal robotic gripper based on the jamming of granular material*” Proceedings of the National Academy of Sciences,* 107(44), 18809-18814.

[45] F. Amend, E. Brown, and B. Roberts, "Granular jamming and vacuum-actuated soft grippers," *Soft Robotics Journal*, vol. 8, no. 2, pp. 92-101, 2016.

[46] M.R. Cutkosky and R.D. Howe, (1990). “Human and Robot Hands: Sensorimotor Control and Object Manipulation”. *MIT Press.*

[47] M.T. Mason, (2018). “Mechanics of Robotic Manipulation”. *MIT Press*, Cambridge, MA. K. Ye and M. Anderson, "Soft robotics: Applications of octopus-inspired grippers in space," *Journal of Soft Robotics*, vol. 11, no. 4, pp. 238-251, 2023.

[48] M.T. Mason, J.K. Salisbury, and A. Harry, (1986). “Robot Hands and the Mechanics of Manipulation”. Cambridge, MA: *MIT Press.*

[49] R. Bogue, (2012). Recent developments in robotic grippers. Industrial Robot”: *An International Journal*, 39(3), 218-223.

[50] R. Deimel. and O. Brock, (2016). “A compliant hand based on a novel pneumatic actuator”. *IEEE International Conference on Robotics and Automation*, 2047-2053.

[51] S.I. Ansary, S. Deb, and A.K. Deb, (2023).” Design and Development of an Adaptive Robotic Gripper”. *Journal of Intelligent & Robotic Systems,* 109(13).

[52] S. Ansary, "Adaptive robotic grippers for space exploration: A review," *Journal of Robotics Research*, vol. 19, no. 3, pp. 144-163, 2023.

[53] G. Iqbal, "Detachable soft robotic grippers with tactile feedback for space environments," *Journal of Smart Robotics*, vol. 16, no. 1, pp. 89-108, 2019.

[54] J. Iqbal, U. Ullah, H. Khan, and A. Ahmad, (2019). “Modular and detachable soft robotic gripper with tactile feedback for human-robot collaboration”. *Sensors*, 19(18), pp. 3928-3945.

[55] T. Kakogawa, "Underactuated soft robotic grippers for high-speed object manipulation in space," *Journal of Autonomous Robotics*, vol. 29, no. 1, pp. 177-192, 2018.

[56] A. Kakogawa, K. Iwata, and S. Sugano, (2018). “Development of an underactuated soft robotic gripper for high-speed object grasping and manipulation”. *IEEE Robotics and Automation Letters,* 3(3), pp. 2451-2458.

[57] C. M. Gosselin, and T. Laliberté, (2008). “Force Analysis and Design of Tendon-Driven Robotic Hands”. *IEEE Transactions on Robotics and Automation*, 24(2), pp.237-245.

[58] A. E. Schultz, and J. Morrow, (2017). “Tendon-driven robots: Control, state estimation, and challenges”. *IEEE Robotics and Automation Magazine*, 14(3), pp. 82-95.

[59] K. Qiu and B. Nelson, "Magnetic actuation in robotic grippers for microgravity," *Journal of Actuation Technologies*, vol. 29, pp. 175-193, 2015.

[60] S. Zhang and G. Diller, "Magnetic-controlled grippers for fine object manipulation in space," *Actuation Systems in Space*, vol. 19, pp. 302-319, 2016.

[61] A. Tottori, A. Kim, and K. Honda, "Miniature robotic systems with magnetic actuation for space applications," *Robotic Gripper Design and Development*, vol. 10, pp. 145-161, 2012.

[62] F. Qiu,. and B.J. Nelson, (2015). “Magnetic helical micro-and nanorobots: Toward their biomedical applications”. *Engineering*, 1(1), 21-26.

[63] S. Tottori, L. Zhang, F. Qiu, K.K., Krawczyk, A. Franco-Obregón, and B.J. Nelson, (2012). “Magnetic helical micromachines: Fabrication, controlled swimming, and cargo transport”. *Advanced Materials*, 24(6), 811-816.

[64] H.C. Berg and R.A. Anderson (1973). “Bacteria swim by rotating their flagellar filaments”. *Nature*, 245(5425), 380-382.

[65] K. Hicks, (2022). “Lockheed Martin Releases Open-Source Interface Standard for On-Orbit Docking.” Available at: https://news.lockheedmartin.com/2022-02-25-Lockheed-Martin-Releases-Open-Source-Interface-Standard-for-On-Orbit-Docking.

[66] M. Winand and S. Gorb, "Biomimetic gripper designs for space missions: Lessons from insect mechanics," *Biological Robotics*, vol. 7, pp. 243-258, 2024.

[67] S.N. Gorb, (2007). “Attachment Devices of Insect Cuticle”. *Springer,* The Netherlands.

[68] A. Monteiro, M. Oliveira, and L. Khairallah, "Topology optimization in robotic gripper design for space," *Additive Manufacturing for Space Exploration*, vol. 9, pp. 145-160, 2023.

[69] R. Sigmund and K. Maute, "Topology optimization for lightweight structures in space grippers," *Journal of Structural Design*, vol. 9, pp. 79-95, 2013.

[70] C. Oliveira, M. Maia, and J. Costa, (2023). “Production of an Office Stapler by Material Extrusion Process, Using DfAM as Optimization Strategy”. *U.Porto Journal of Engineering*, 9(1), pp.28-41.

[71] G. Averta, C. Della Santina, F. Ficuciello, M.A. Roa, and M. Bianchi, (2021). “Planning, Control, and Perception of Soft Robotic End-Effectors”. *Frontiers in Robotics and AI,* 8:795863.

[72] S. A. Khairallah, A.T. Anderson, A. Rubenchik, and W.E. King, (2016). “Laser Powder-Bed Fusion Additive Manufacturing: Physics of Complex Melt Flow and Formation Mechanisms of Pores, Spatter, and Denudation Zones.” *Acta Material*, 108, pp.36-45.

[73] K. Ye and M. Anderson, "Soft robotics: Applications of octopus-inspired grippers in space," *Journal of Soft Robotics*, vol. 11, no. 4, pp. 238-251, 2023.

[74] Space Applications Services (2024). HOTDOCK®: A Multifunctional Coupling Interface for Space and Non-Space Applications. Available at: https://www.spaceapplications.com/products/mating-demating-device-hotdock

[75] J. Mahler, J. Liang, S. Niyaz, M. Laskey, R. Doan, X. Liu, J. Ojea, and K. Goldberg, "Dex-Net 2.0: Deep learning to plan robust grasps with synthetic point clouds and analytic grasp metrics," *Robotics: Science and Systems (RSS)*, 2017.

[76] D. Kalashnikov, A. Irpan, P. Pastor, J. Ibarz, A. Herzog, E. Jang, and S. Levine, "QT-Opt: Scalable Deep Reinforcement Learning for Vision-Based Robotic Manipulation," *Proceedings of the 2018 Conference on Robot Learning (CoRL)*, pp. 651-673, 2018.

[77] J. Sundaralingam and M. Hermans, "AI-enhanced robotic grippers for space: Learning-based approaches," *Robotics and Machine Learning Journal*, vol. 14, pp. 121-138, 2018.

[78] S. Shintake, E. Schlagenhauf, and S. Rus, "The application of soft robotics in space: Gripper designs for delicate object handling," *Advances in Robotics Research*, vol. 8, no. 3, pp. 211-223, 2018.

[79] H. Kim, T. Shibata, and M. Takeuchi, "Novel materials in soft robotics: Applications in space grippers," *Materials Science & Engineering Journal*, vol. 17, pp. 82-94, 2019.

[80] T. Ronneberg, C.M. Davies, and P.A. Hooper, "Revealing Relationships between Porosity, Microstructure and Mechanical Properties of Laser Powder Bed Fusion 316L Stainless Steel through Heat Treatment," *Materials & Design*, vol. 189, p. 108481, 2020.

[81] J. Sugavaneswaran, "Additive manufacturing and robotic gripper designs for space," *Manufacturing and Space Exploration Journal*, vol. 15, pp. 94-111, 2020.