ADDITIVE MANUFACTURING OF RECONFIGURABLE MODULES FOR LUNAR IN-SITU RESOURCE UTILIZATION.

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Introduction: A sustained lunar presence requires autonomous, adaptable systems. Traditional robotic designs are limited by predefined functions and logistics, whereas reconfigurable modules (RM) can dynamically adapt, self-repair, and optimize functionality. RM-based robotics enable lunar infrastructure development and In-Situ Resource Utilization (ISRU) operations, including power generation, mapping, and resource processing [1]. Additionally, RM systems can self-replicate [2], exponentially increasing ISRU operations over time. Additive manufacturing (AM) offers an efficient way to build electromechanical systems, especially in resource constrained environments like the Moon. Lunar-derived feedstock can be used for on-demand production of structural components and functional modules, reducing dependency on Earth-based supply chains, and enhancing adaptability. Autonomous 3D printing, assembly, and part replacement would extend the operational lifetime of lunar robotic systems, mitigate environmental challenges, and support scalable lunar operations. This paper presents a 3D-printed RM as a first step towards this technology. Comprising a DC motor, coupling mechanism, and electronic control circuitry, this unit serves as a foundational building block for constructing complex robotic systems from lunar resources.

Background: Additively manufactured RMs are beneficial as the repeated modules can be optimized to reduce required resources which aid in lowering costs [3]. Additionally, complex robot systems created using RMs would be capable of achieving a wider variety of tasks by self-rearranging the individual modules [3]. These advantages of RMs enhance the robotic system's robustness and versatility. These benefits can be applied to lunar ISRU operations where RMs could switch between different roles, eliminating the need for multiple dedicated robots, for example:

- Excavation mode: forms a long, articulated structure for resource extraction.
- Transportation mode: reconfigures into a wheeled or snake-like form for mobility.
- Assembly mode: rearranges into rigid structures for construction.

Three common architectural groups are considered when designing RM systems: lattice, chain, and mobile [3]. Lattice consists of units that are arranged in regular 3D patterns, chain is composed of units that form serial connections, and mobile has units that maneuver around the environment and join to form secondary robots [3].

Reconfigurable Modules: In order to create a RM through AM processes, a chain-architecture was selected due to the simplicity of its serially connected modules. These connections allow the robotic system to morph dynamically for different tasks, permitting movement in any position or orientation [3]. The RM was split up into three main components: DC motor, coupling mechanism, and electronic control circuitry.

DC Motor. The motor converts electrical energy into mechanical rotational energy, allowing the RM to actuate other modules. A 3D-printed brushed DC motor was chosen for its simple components and structure, consisting of permanent magnets, windings, rotor, stator, and commutator.

The permanent magnets were 3D-printed via Selective Laser Sintering (SLS) using an MQP-S-11-9 spherical powder ($Nd_{7.5}Pr_{0.7}Fe_{75.4}Co_{2.5}B_{8.8}Zr_{2.6}Ti_{2.5}$). The windings used 1mm Cu wire, while the rotor and stator were printed via Fused Deposition Modeling (FDM) using high-carbon iron filament. This filament is 75% to 80% iron by mass, which is important in increasing the generated magnetic field of the motor. The commutator was made from the PLA filament and wrapped in a thin copper sheet to make it conductive. The components were assembled to create a brushed DC motor for the RM (Figure 1).

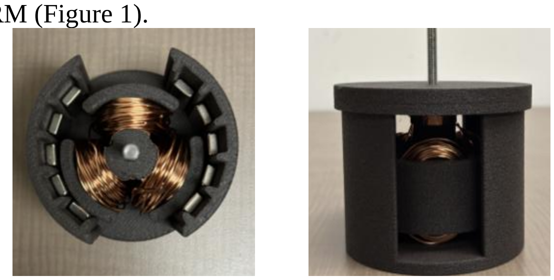

Figure 1. Assembled brushed DC motor for RM

DC motors for RM could be manufactured from lunar resources. Structural components like casings or frames could be made of lightweight materials such as Al from lunar anorthite or Ti from lunar ilmenite. The electromagnetic core could use Fe from ilmenite, pyroxene, or Fe oxides, while Si could enable silicon steel production, offering high magnetic permeability and reduced eddy current losses. Lunar hard magnets could be produced using alnico (Fe and Al from lunar regolith, Ni and Co from metallic meteorites). Rare earth magnets such as NdFeB or SmCo could be sourced from lunar KREEP deposits. As lunar materials lack naturally occurring Cu, Al is a promising material for motor windings due to its good electrical conductivity.

Coupling Mechanism. The coupling mechanism enables mechanical linking of individual RMs. Different designs exist, including electromagnetic and mechanically actuated coupling [4]. Common connectors applicable for space robotics are ACOR and DRAGON [5, 6], both of which feature a Shape Memory Alloy (SMA) actuator for connection [4]. A preliminary coupling mechanism inspired by the ACOR connector was 3D-printed and tested, consisting of a PLA base plate and 4 flexible TPU latches. An SMA wire wound through the latches, contracted when the system was powered causing inward inflection (Figure 2). This design minimized moving parts but achieved only 1mm of displacement.

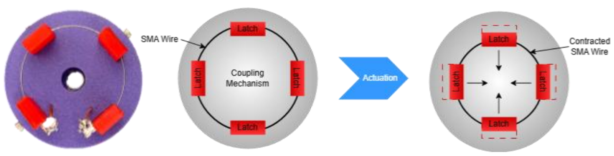

Figure 2. SMA wire-actuated 3D-printed coupling mechanism

The design was adapted to use SMA springs to actuate the latches along linear rails, as the coil structure provides a larger displacement. The latches and rails were 3D-printed in PLA (Figure 3). While this design contained more moving parts, it achieved a higher displacement of 4mm, making it more suitable for RM.

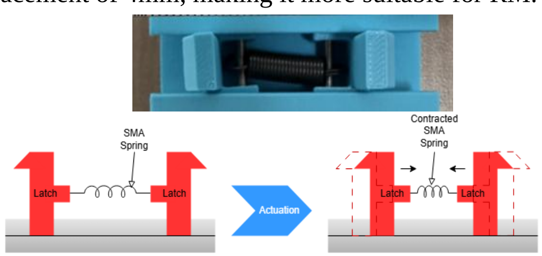

Figure 3. SMA spring-actuated 3D-printed coupling mechanism.

Electronic Control Circuitry. The RM emphasizes on using only basic electronic components such as op-amps, to ensure that the circuit can be completely manufactured in space without requiring significantly complex processes. The circuit focused on open loop control for the DC motor using a PWM generator (Figure 4).

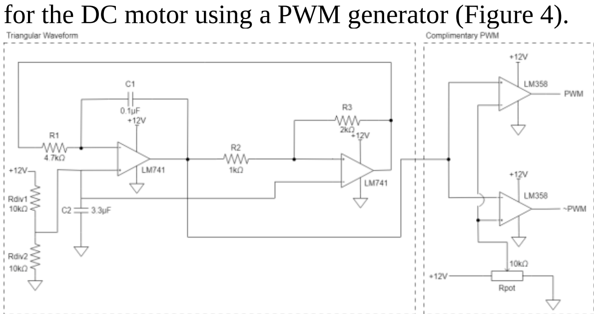

Figure 4. Electrical Schematic of PWM Generator

This signal was then fed through an H-Bridge circuit to control the DC motor rotational direction (Figure 5).

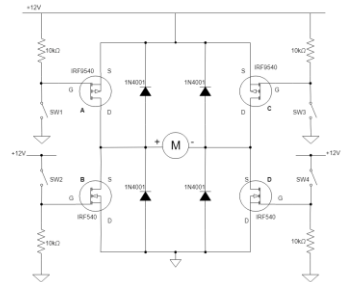

Figure 5. Electrical Schematic of H-Bridge

The coupling mechanism control circuitry used a resistive control strategy [7] along with an SR latch to turn off the SMA when fully actuated (Figure 6).

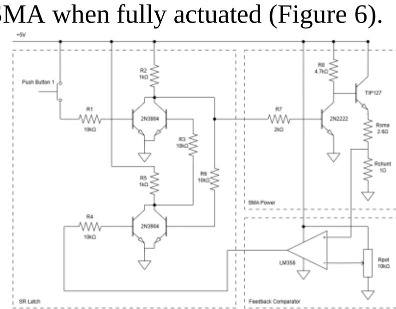

Figure 6. Electrical Schematic of SMA Control Circuit

Conclusion: This study demonstrates the feasibility of 3D-printed RMs consisting of a brushed DC motor, an SMA spring-actuated coupling mechanism, and electronic control circuitry. This research represents a critical step toward enabling modular assembly and reconfiguration while also highlighting the potential of AM for space robotics. Each component of the RM can be fabricated from lunar-derived materials. By leveraging ISRU and AM, these modular robotic systems could enable adaptive and scalable infrastructure development, while extending operational lifetimes, critical for a sustained presence on the Moon.

References:

[1] Sanders G. B. et al. (2024) *AIAA Aviation Forum and Ascend 2024*. [2] Zykov V. et al. (2005) *Nature, 435*, 163-164. [3] Seo J. et al. (2019) *Annu. Rev. Control Rob. Auton. Syst.*, *2*, 63-88. [4] Ellery A. and Elaskri A. (2024). *Preprints.* [5] Badescu M. and Mavroidis C. (2003) *IEEE/ASME Trans. Mechatron.*, *8*, 342-351. [6] Nilsson M. (2002) *IEEE Int. Conf. Robot. Autom.* [7] Berhil A. et al. (2023) *J. Intell. Mater. Syst. Struct.*, *34*, 1097-1103.

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