MAR5-R

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***Abstract*—Long-duration human missions to Mars present unprecedented challenges in resource management, particularly in dealing with the significant accumulation of inorganic waste. An eight-person crew on a three-year mission is expected to generate approximately 12,600 kilograms of non-biodegradable materials, including packaging, textiles, and structural components. Returning this waste to Earth or sending frequent resupply missions is neither economically nor logistically viable, highlighting the need for sustainable, closed-loop waste management systems.**

This project proposes a comprehensive approach based on the principles of recovery, redesign, recycling, reduction, and reuse. The framework aims to transform waste into valuable resources by incorporating circular design strategies, in-situ recycling technologies, and multifunctional material applications. As a complementary innovation, the project also introduces the development of an automated classification system capable of distinguishing metallic from polymeric waste. This system leverages electromagnetic sensing and advanced computer vision, utilizing a Raspberry Pi 4 single-board computer as its core. The Raspberry Pi 4 allows the system to run more complex and robust Deep Learning Models for material identification, ensuring efficient separation and preparation of materials for further processing.

By integrating sustainable logistics with automated classification technologies, the project contributes to reducing dependence on Earth-based supplies, enhancing habitat autonomy, and supporting the long-term feasibility of human presence on Mars and beyond. The proposed system represents a crucial step toward truly self-sufficient interplanetary missions, where waste becomes a strategic resource rather than a burden.

***Index Terms*—Mars exploration, space missions, sustainable, inorganic waste, circular economy in space, resource recovery, material redesign, recycling technologies, reuse strategies, waste reduction, automated waste classification, electromagnetic sensing, polymer detection, computer vision, Raspberry Pi 4, sensor fusion, robotic waste handling, additive manufacturing, structural reuse, life-support systems, resilience of extraterrestrial habitats, space technology innovation.**

I. Introduction

Human exploration of Mars introduces not only unprecedented technological and scientific challenges but also critical logistical and environmental considerations. Among these, waste management stands out as a major concern. Over the course of a three-year mission involving an eight-member crew, it is projected that approximately 12,600 kilograms of inorganic waste, primarily consisting of packaging materials, textiles, and structural components, would be generated. This accumulation is far from trivial: on Earth, waste is disposed of through established infrastructure, but in space, such volumes become an operational burden. Attempting to return this material to Earth or continuously deliver new resources from Earth would be both economically prohibitive and unsustainable given the high costs of launch and transport.

The challenge, therefore, is not simply one of storage but of reimagining waste as a potential resource. By developing systems that can manage, reuse, and recycle inorganic materials directly on the Martian surface, future missions can reduce their dependence on terrestrial resupply chains. Such systems would also contribute to creating more autonomous and resilient habitats, supporting crew health and safety while optimizing resource utilization. Furthermore, the implementation of sustainable waste management technologies aligns with broader goals of establishing a long-term human presence beyond Earth, where closed-loop resource cycles will be indispensable.

This project seeks to explore innovative solutions for transforming inorganic waste into functional assets—whether through repurposing materials for construction, processing them into new structural elements, or integrating them into life-support infrastructure. In doing so, it aims to advance the feasibility and sustainability of crewed missions to Mars and set the groundwork for future exploration of even more distant destinations.

II. Objectives

The overarching goal of this project is to establish a comprehensive, sustainable, and resilient logistics system for the management of inorganic waste generated during long-duration space missions. This system seeks to transform discarded materials into valuable resources by applying the principles of recovery, redesign, recycling, reduction, and reuse. In doing so, it will ensure that waste is not treated as a liability but as an integral component of mission sustainability.

This framework is designed to transform discarded materials into valuable resources through the following strategies:

A. *Recover*

Develop efficient methods for collecting, classifying, and storing inorganic waste generated during the mission. Establish handling and safety protocols to ensure that no material is lost and that all waste remains available for future use.

B. *Redesign*

Develop efficient methods for collecting, classifying, and storing inorganic waste generated during the mission. Establish handling and safety protocols to ensure that no material is lost and that all waste remains available for future use.

C. *Recycle*

Implement technologies to process inorganic waste into usable raw materials directly on the Martian surface. Transform plastics, metals, and composites into inputs that can support additive manufacturing, habitat maintenance, or the production of spare parts.

D. *Reduce*

Limit waste generation at the source by optimizing mission logistics and supply chain design. Prioritize the use of reusable or multifunctional components to decrease dependency on single-use items and reduce resupply needs from Earth.

E. *Reuse*

Develop adaptive systems that extend the lifecycle of mission materials by giving them secondary applications. Packaging, textiles, and structural elements should be reconfigured to serve roles such as storage containers, construction blocks, or habitat reinforcements.

Together, these strategies aim to minimize reliance on costly Earth-based resupply missions, while increasing the autonomy, efficiency, and resilience of extraterrestrial habitats. In this way, inorganic waste becomes a strategic resource that supports the sustainability of human presence on Mars and lays the foundation for future interplanetary exploration.

III. State of Art

A. *Dual Use of Packaging on the Moon: Logistics-2-Living (L2L)*

The primary obstacle in space missions is the cost and mass of everything launched into orbit, where every extra kilogram carries an immense price tag. A significant portion of this weight comes from packaging and containers which traditionally become unusable waste upon arrival. To radically address this waste, the Logistics-2-Living (L2L) system was developed to transform cargo packaging—primarily the standard CTB (Cargo Transfer Bags) currently used on the International Space Station—into reusable components for a lunar habitat. The core concept is dual-use design: after being emptied, these logistics bags and their rigid metal inserts are reconfigured into essential habitat infrastructure, such as internal divisions, furniture, and storage (tables, chairs, bunks, cabinets, partitions). The metallic inserts are reused as structural pieces for shelving or desks. Furthermore, the empty bags can be unfolded into panels to serve as internal walls, or even as radiation shielding, particularly if they are manufactured with hydrogen or water-impregnated materials. Empty packaging can also be filled with regolith (lunar soil) to form sandbag-like protective berms or even pavement. Advanced proposals include versions with flexible solar cells built-in, allowing the empty bags to function as supplemental power panels. Ground tests, such as the D-RATS simulation in Arizona, have already validated the L2L concept, where astronauts successfully converted a set of empty bags into a fully functional geoscience laboratory complete with work tables and glove compartments. Studies project that in a long-term lunar mission, between 1,300 and 1,700 CTB bags would be used, and if all were recycled via the L2L scheme, space waste would be reduced nearly to zero, while simultaneously saving up to 1,600 kg of mass in furniture and structural elements that would no longer need to be launched from Earth. L2L essentially acts as a bridge between Class II construction (kit-of-parts assembled on-site) and Class III construction (structures made from local materials, like regolith), offering a robust, modular, and mass-saving strategy for sustainable lunar habitation. [1]

B. *Waste Management Options for Long-Duration Space Missions: When to Reject, Reuse, or Recycle*

The standard practice of packing and incinerating waste upon re-entry, currently used on the ISS, is unsustainable and infeasible for long-duration missions to locations like the Earth-Moon L2 point or Mars, where waste accumulation poses serious risks (volatiles, contamination, and dead mass). To address this, various disposal options were evaluated, starting with direct rejection (ejecting compacted "trash footballs" into space). This method was deemed impractical and risky because liquids sublimate and recondense, potentially contaminating the spacecraft, and the complex orbital dynamics at L2 could cause frozen debris to collide with the habitat. Therefore, the study concludes that energy recycling—converting waste into useful gases—is the most promising solution. This process involves using reactors (like pyrolysis or gasification) to transform trash via two main paths: Trash-to-Gas (TtG), which generates simple gases (CO, CO_2, CH_4, H_2) suitable for low-thrust propulsion (resistojet); and Trash-to-Supply-Gas (TtSG), a more complete process that yields highly valuable propellants like oxygen (O_2) and methane (CH_4). This closed-loop system offers significant benefits: for a long mission at the L2 Gateway, it could generate up to 990 kg of recycled propellant, saving between 1,300 and 3,300 kg of launch mass from Earth. This recycled fuel is sufficient to cover the station-keeping needs for an entire year or even power small landers for lunar exploration. Ultimately, converting waste into propellants not only eliminates the risk of accumulating garbage but also allows the mission to become self-sustaining, resulting in missions that are both cheaper and safer. [2]

C. *In-Space Manufacturing: Pioneering a Sustainable Path to Mars*

Recent advancements in in-space materials recycling and reuse technologies have emerged as critical enablers for long-duration space missions. Over the past decade, multiple initiatives supported by NASA and associated research programs have sought to reduce material waste, improve logistics efficiency, and enhance the sustainability of additive manufacturing (AM) processes in microgravity environments.

In 2015, the Small Business Innovation Research (SBIR) program initiated efforts toward the development of common-use recyclable materials for International Space Station (ISS) packaging. This project established a foundation for incorporating sustainable materials engineering principles into space logistics.

Subsequently, in 2018, another SBIR project introduced the ReFabricator, a payload designed to recycle used or failed 3D-printed parts into reusable feedstock for AM. This technology demonstrated the feasibility of closed-loop polymer recycling in orbit, reducing reliance on Earth resupply missions.

Building upon these initiatives, the In-Space Manufacturing (ISM) program supported a faculty fellow study in 2019 (Sarker), which analyzed technical challenges and opportunities related to recycling processes in space, including material degradation, contamination control, and energy efficiency.

From 2020 to 2023, ISM sponsored additional analyses conducted by Blanchard and Kimbrel at CMC, focusing on material recyclability and mechanical performance under repeated recycling cycles. Their work provided empirical data essential for validating the long-term viability of polymer reuse in closed environments.

In 2022, through the Cooperative Agreement Notice (CAN) program, the University of Nebraska Omaha investigated the sterilization and verification of recycled AM components, ensuring that reprocessed materials meet safety, structural integrity, and contamination control standards suitable for human-rated systems.

More recently, in 2024, NASA initiated two complementary efforts. The Crowdsourcing Contenders program solicited innovative concepts and approaches for recycling mission-generated waste materials, promoting cross-disciplinary participation in developing novel waste-to-resource conversion solutions. Concurrently, an Internal Research and Development (IRAD) project focused on the in-house development of a polymer recycling system, including process control and system integration for next-generation spacecraft manufacturing modules.

Collectively, these initiatives represent the current state of the art in in-space recycling technologies. They establish a progressive trajectory from material design and characterization to system-level integration, highlighting the growing importance of closed-loop material management, additive manufacturing sustainability, and autonomous resource utilization in support of long-duration human exploration missions. [3]

IV. What is MAR5-R

In the pursuit of sustainable exploration beyond Earth, resource management has become one of the greatest challenges faced by future space missions. To address this issue, our team has developed MAR5-R, a circular economy model specifically designed for extraterrestrial environments. The name MAR5-R derives from Mars, symbolizing our commitment to interplanetary sustainability, while replacing the final "S" with a "5" to represent the five core principles of our framework: Recover, Redesign, Recycle, Reduce, and Reuse.

The MAR5-R system proposes an integrated approach to minimize waste generation, optimize material usage, and extend the functional life of mission resources. By applying the five R's, it seeks to establish a closed-loop system where every material can serve multiple purposes across the mission's duration—drastically reducing dependency on Earth-based resupply and supporting long-term human presence on other planets.

Within this framework, one of our key developments is the creation of modular, multifunctional components capable of being reused and reconfigured throughout the mission. These components exemplify the MAR5-R philosophy by transforming traditional single-use materials, such as packaging or structural supports, into versatile modules that can be assembled into furniture, partitions, insulation panels, or repair materials. Through intelligent design and material selection, the system not only promotes sustainability but also enhances astronaut autonomy and operational efficiency in resource-limited environments.

This concept represents more than an engineering innovation—it is a step toward redefining the way humanity interacts with matter in space. MAR5-R embodies a circular mission economy, where waste becomes opportunity, and sustainability becomes an inherent part of exploration.

Traditional packaging and equipment housings used in space missions are typically single-use and contribute significantly to inorganic waste accumulation. In contrast, our system seeks to transform these materials into modular elements capable of being reconfigured and repurposed multiple times throughout the mission, addressing both functional and environmental objectives simultaneously.

Each modular piece is designed following principles of mechanical simplicity, material efficiency, and functional versatility. The modules can be assembled and disassembled without specialized tools, allowing astronauts to reconfigure them according to situational requirements—ranging from constructing furniture and storage units to building interior partitions, thermal barriers, or protective layers within the habitat. This adaptability provides a flexible infrastructure that evolves with the mission's progression and changing crew needs.

The proposal aligns directly with the sustainability framework based on the five R's: Recover, Redesign, Recycle, Reduce, and Reuse, integrating them as guiding principles for design and implementation:

- **Recover**: All components are designed for easy retrieval after their initial use. The modular design enables efficient disassembly and compact storage, ensuring no valuable material is wasted. Recovery protocols will facilitate inventory control and maintain material traceability within the mission's logistical system.
- **Redesign**: The modules adopt a multifunctional design philosophy, allowing each component to fulfill several roles throughout its lifecycle. Packaging structures used for equipment transport can be redesigned and reassembled as operational furniture, workstations, insulation panels, or even repair materials for structural maintenance. This continuous redefinition of purpose ensures maximum material utility across mission stages.
- **Recycle**: Once a component reaches the end of its functional lifespan, it can be recycled using in-situ processing techniques. Modular parts made from recyclable polymers or lightweight alloys can be shredded and reprocessed through additive manufacturing systems, providing raw material for the creation of new components or tools, thus maintaining a closed-loop resource cycle within the habitat.
- **Reduce**: The modular system inherently reduces the total mass and volume of materials that must be launched from Earth. By consolidating multiple functions into a single modular standard, the need for redundant or single-purpose equipment diminishes. This results in lower payload requirements, reduced launch costs, and a smaller environmental footprint for interplanetary logistics.
- **Reuse**: Durability and compatibility are central to the reuse of these modules. Through standardized interfaces and modular geometries, each piece can be reassembled into a variety of configurations depending on the habitat's spatial or operational needs. A single module may begin its life as cargo packaging, later function as a storage compartment, and eventually serve as a thermal or radiation shield—extending its lifecycle and overall mission value.

The development of these modular components not only provides a practical solution for waste minimization but also enhances mission autonomy, safety, and adaptability. By turning packaging and structural waste into functional building materials, the system redefines the concept of "trash" in space environments, transforming it into an essential resource for survival and comfort.

Ultimately, this approach contributes to the creation of self-sustaining habitats where materials circulate within a closed ecosystem, reducing dependency on Earth-based resupply and advancing the long-term feasibility of human presence on Mars and beyond.

V. Autonomous Waste Classification System

In addition to the implementation of sustainable logistics principles, this project seeks to develop an automated system for the classification of inorganic waste into metallic and polymeric categories. The proposed system will combine electromagnetic sensing with advanced computer vision, using a **Raspberry Pi 4** single-board computer as its core processing unit. Metallic residues will be identified through variations in electromagnetic response, while polymers will be distinguished through visual analysis enhanced by Deep Learning. The integration of both methods will allow robust classification even under conditions of dust, irregular shapes, or mixed materials. Once classified, the system will trigger actuators to separate the items into their designated storage compartments, while simultaneously recording operational data for further optimization. This approach contributes to the overall recycling and reuse strategy by enabling efficient preprocessing of materials, reducing manual intervention, and laying the groundwork for closed-loop resource management in extraterrestrial habitats.

This system is a low-cost, automated classifier designed to perform the initial (primary) separation of waste, focusing on distinguishing between metals and polymers (plastics). Its core principle relies on sensor fusion for maximum reliability.

*1) **Scope and Operational Flow**:* The goal is to take mixed pieces entering via a chute or mini-conveyor belt and quickly direct them to the correct bin (metal or polymer).

- Input: Waste pieces with irregular shapes and potential dirt/grime.
- Processing: Simultaneous electromagnetic reading and image capture.
- Decision: An algorithm uses the combined sensor information to determine the destination.
- Output: Activation of an actuator (servomotor or solenoid) to divert the piece.
- Operation: The system is autonomous, operates with low latency (i.e., very fast), and is designed to tolerate the typical dust and ambient magnetism of enclosed habitats.

*2) **Detection Principle: How It Knows What It Is**:* The system uses two complementary detection methods:

- Primary Classification: Electromagnetic Signal (Inductive Sensor) This is the fastest detection method, based on the physics of metal conductivity.
  - Metals: When a metal piece passes an detection coil excited with an alternating current (AC) signal, the varying magnetic field induces eddy currents within the metal. These currents, in turn, generate an opposing magnetic field. The measurable result is a change in the impedance (amplitude and phase) of the detection coil.
  - Polymers/Plastics: These materials are non-conductive, so they do not generate eddy currents, and the inductive coil signal remains virtually unchanged.

  Implementation: An AC signal (several kilohertz, kHz) is injected, and the change in the coil is measured using a detection circuit and the ADC (Analog-to-Digital value clearly above a threshold is classified as Metal.

Converter) which interfaces with the **Raspberry Pi 4**. A value clearly above a threshold is classified as Metal.

- Confirmation and Secondary Classification: Computer Vision (**Raspberry Pi 4**) The camera is utilized when the inductive signal is ambiguous or more detail is needed:
  - Validation: It captures an image of the piece to confirm the electromagnetic reading (e.g., to rule out false positives from external fields).
  - Polymer Classification: If the inductive signal indicates "Non-Metal" (a polymer candidate), the image is used for secondary classification (e.g., distinguishing clear, white, or specific types of plastic, if required).
  - Processing: A robust **Deep Learning Model (CNN)** is run directly on the powerful **Raspberry Pi 4** for high-accuracy visual inference and to increase robustness against false positives.

VI. Development

The development of our project began at the very start of the hackathon, where every member of the team felt somewhat uncertain—understandably so, as it was our first time participating in an event of this kind. After receiving the initial instructions, we held a brief meeting to discuss how we would organize ourselves to carry out the project. Once the roles were defined, we moved on to brainstorming. The ideas at that stage were scattered and lacked coherence, mostly because none of us had yet reviewed the full documentation. We therefore dedicated several hours of the first afternoon to conducting research, reading the official materials, taking notes, and preparing concepts to guide the project's development. Around midnight, we reconvened with a clearer understanding of the challenge requirements. From there, we arrived at the concept presented in this document.

That concept became MAR5-R, our proposal for a self-sustaining recycling system. Through the use of pre-designed modular components, the system allows for the creation of containers intended for space missions. Once these containers have served their purpose, they can be disassembled and repurposed into new structures, tools, walls, and other elements. This is made possible by a simple rail-based design that not only enables quick assembly and disassembly but also ensures structural strength, safety, and usability under conditions different from those on Earth.

However, since our team is composed of students in Robotics Engineering and Embedded Systems, we decided to complement the proposal with a circuit capable of separating metals from polymers using electromagnetic waves, controlled through a Raspberry Pi 4.

After developing the concept, we began turning it into reality. Ronaldo took charge of the design and 3D printing of the modular components. Sergio, Jarol, and Sebastián handled the circuit's construction and testing. Meanwhile, Diego and Paolo focused on documentation, the final pitch, and this written report, while also contributing to key decision-making and assisting in both the circuit assembly and 3D design process.

During the early hours of the second day, our concept began to take tangible form, drawing the attention of attendees, mentors, guests, and even other participants. The rest of the day was dedicated to testing, redesigning certain components, and preparing the final presentation.

That night, things took an unexpected turn when documentation became the team's top priority. Everyone contributed to writing and refining it while progress continued on the physical prototype.

By around 4 a.m., we had completed the project, leaving only a few final revisions before submission.

VII. Evidence

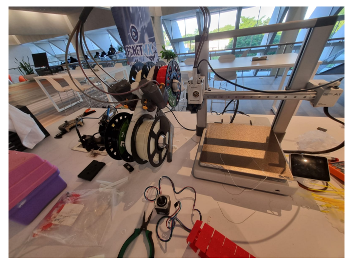

Fig. 1. Ready to start printing

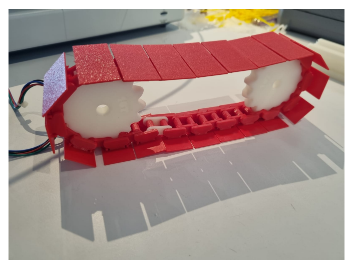

Fig. 2. Fundamental part of the Autonomous Waste Classification System

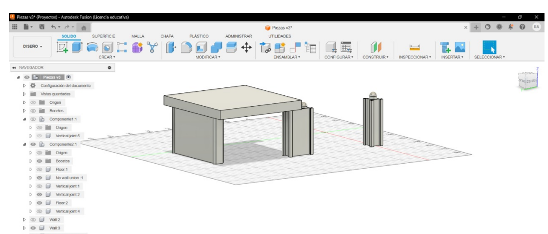

Fig. 3. Design of the modular achitecture

VIII. Results

Throughout the development of our proposal, we achieved results that went beyond our initial expectations, both in the technical and conceptual aspects of the project. By combining our knowledge in robotics, embedded systems, and design,

Fig. 4. Raspberry Pi4 in the final case

we successfully created a functional prototype that demonstrated the core principles of the MAR5-R system and the Autonomous Waste Classification System.

The modular design of MAR5-R proved to be efficient, stable, and adaptable. The 3D-printed, despite having tolerance issues, we demonstrated that our proposal, when properly developed, has the potential to be validated the feasibility of creating reconfigurable containers and structures that could be easily assembled and disassembled under simulated space conditions. This confirmed the potential of our rail-based approach as a practical solution for sustainable material reuse in extraterrestrial missions.

In parallel, the electronic circuit designed for automated waste separation delivered promising results. Using electromagnetic signals processed through a Raspberry Pi 4, the system was able to distinguish between metallic and polymeric materials with consistent accuracy. These tests validated our concept of integrating intelligent classification mechanisms into a compact and energy-efficient platform suitable for autonomous operations.

Beyond the technical milestones, one of the most valuable outcomes was the development of teamwork and adaptability under high-pressure conditions. The coordination between design, electronics, and documentation allowed us to meet all objectives within the 72-hour hackathon timeframe. Our prototype not only functioned as intended but also attracted the attention of mentors and participants, reinforcing the innovative potential of our proposal.

IX. Conclusion

Development of a project is never an easy task, once started, more often than not one may find themselves hit with roadblocks and potholes that make continuing both tedious and hard. MAR5-R and it's team were no exception, with having the mission to create a solution for the very specific hypothetical situation given by the challenge was no easy task. Thankfully, and with the help from the team and advisers from the NASA Space App Challenge, the project was able to be completed.

To conclude, every member of our team gained a valuable experience. Despite it being our first hackathon, we believe we performed remarkably well, so much so that we are confident we can compete with other teams. Without a doubt, this event left us with important lessons and a strong motivation to continue developing our project and to participate in future hackathons.

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