Design of an AI Trash Sorting Machine for Use on the Moon and Mars

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AI TRASH SORTING FOR SPACE MISSIONS

Overview and Introduction

AI in Waste Sorting

AI and ML improve waste sorting by integrating robotics and self-learning algorithms for precise material classification.

- Artificial intelligence (AI) refers to the ability of computers to simulate human thought and perform tasks in real-world environments.
- Machine learning (ML), a subset of AI, encompasses the technologies and algorithms that enable systems to identify patterns, make decisions, and improve performance through experience and data.

Space Mission Relevance

AI-driven sorting is essential for Mars and lunar missions to recycle materials and reduce costly supply needs.

Technological Innovations

Terrestrial AI technologies like advanced sensors and ML models enable high accuracy and adaptability in sorting.

Challenges in Space

Challenges include low-gravity (compared to Earth), dust contamination, radiation, extreme environments, and strict system mass, volume, and power constraints.

ECONOMIC CONSIDERATIONS

Mars and Lunar Mission Costs

Mars

Difficult to assess due to the large number of uncertainties involved such as including development or just operational costs. Cadence is also a important – the more missions to Mars, the lower the cost.

Estimate using Mars Perservence Rover:

- Landed mass of 1,025 kg
- Total cost $2.7B
  - Spacecraft Development $2.2B
  - Launch Services $243M
  - Operations/Scientific Analysis $300M

Using just launch services **$237,073/kg.** For crewed missions, launch service costs will be **higher**.

Moon

Using chemical rockets the estimated cost is $1M to $1.2M to fly a single kilogram from Earth to the Moon.

Costs will decrease as the number of Moon missions increases

NASA's Launch Services Pprogram functions as a broker, matching spacecraft with the best-suited rockets, managing the launch process, providing support from pre-mission planning to post-launch. It operates under the Space Operations Mission Directorate (SOMD)

ENVIRONMENTAL CHALLENGES

Surface and Habitat Conditions

Habitat Environmental Challenges

Ideally sorting occurs inside a habitat

Pressurized habitats mimic Earth-like atmospheres (14.7 psi, 21% O_2) but may increase fire risks due to altered pressures and oxygen levels like those used on the Shuttle (10.2 psi 26.5% O_2).

Extreme Surface Conditions

Mars and lunar surfaces have extreme temperatures, low pressures, and high radiation levels challenging robotic operations.

Material and Mechanical Protection

AI sorting systems require sealed housings, dust-resistant materials, and hardened electronics for 20-year operation.

Engineering Design Considerations

Thermal control, sensor choice, and mechanical reliability are critical for long-duration surface mission success.

Environmental Conditions Table

	MARTIAN SURFACE	LUNAR SURFACE	INSIDE A PRESSURIZED HABITAT
Gravity	3.73 m/s^2	1.625 m/s^2	Same as external surface
Atmospheric pressure	636 Pa	0.3 nPa	57.2 kPa
Temperature range	-153°C to 20°C	-223°C to -23°C	18°C to 27°C
Atmospheric composition	95% CO2, 2.7% N2, 1.6% Ar, trace gases	N/A	~34% O2, 66% N2
Radiation	40–50× Earth	~200× Earth	To be determined
Soil composition issues	Regolith w/ perchlorates, dust	Charged, sharp dust	N/A

WASTE GENERATION IN SPACE

Crew Waste Stream

Varied Crew Waste Types

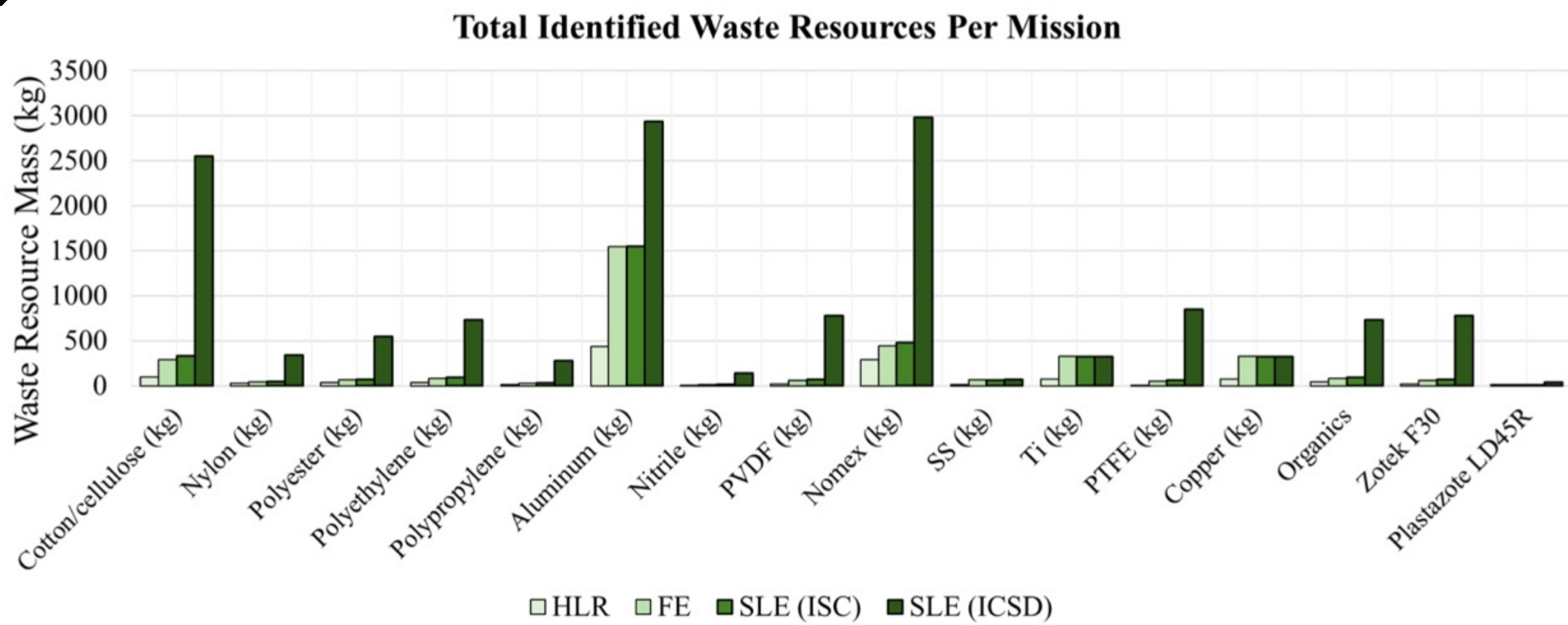
Crewed missions generate diverse waste including food packaging, clothing, hygiene products, and metallic tools daily.

Waste as Recycling Feedstock

Polymers, textiles, biologics, and metals in crew waste can be valuable feedstocks for recycling and in-space manufacturing.

Examples of Crew Trash Items

Trash Component	Trash Component	Trash Component
Athletic Running Shoe	Cotton T-shirts	Beef Patty
Shorts	Towels	Scrambled Eggs
Socks	Wet Wipes	Beef Franks
Leather Belt Buckle	Dry Lab. Chem Wipes	Macaroni
Exercise Shirt	Disinfectant Wipes	Tortilla
Thermal Protective Glove	Nitrile Gloves	Rice Pilaf
Electric Shaver	Shampoo On Towels	Sweet And Sour Chicken
Adjustable Tether	Toothpaste On Towels	Cream Spinach
Mini Flashlight	Polyethylene Terephthalate (PET) Plastic	Orange-Pineapple Drink
Flashlight Nylon Belt Holster	Chewing Gum	Apple Cider Drink
Mechanical Pencil	Deodorant	Pineapple Drink
Binder Clips	Computer Paper	Dried Apricots
Rubber Bands	Duct Tape	Peaches
HEPA Filter (Vacuum Filter)	Polyimide Tape	Macadamia Nuts
Vacuum Bags	Hook And Loop Backing	Strawberries
Open End Wrench	Bite Size pouch	Vanilla Pudding
Scientific Calculator	Thermo pouch	Reclosable Plastic Bag
Magnetic Strip Assembly	Beverage Pouch	Bubble Wrap
Nylon Brush	Septum	Syringes
Oxygen Sensor	Septum Adapter	Bandages
pH Strips	Rehydrateable Pouch	Bulk overwrap bag (BOB)
Dessicant	Overwrap, White	



Lunar Segments of the Moon to Mars Architecture:
Human Lunar Return (HLR)
Foundational Exploration (FE)
Sustained Lunar Evolution (SLE) reference missions:
Increased Science Capability (ISC)
Increased Crew Size and Duration (ICSD)

Reference: Pitts, R. P., Alvarez, V. R. Ewert, M. K. and Spader, A. M. “Advanced Waste Management Strategic Analysis: Human Lunar Return to Sustained Lunar Evolution,” Jul. 2025, Accessed: Aug. 12, 2025. [Online]. Available: https://hdl.handle.net/2346/102765

EQUIVALENT SYSTEM MASS (ESM)

Importance of ESM in System Design

Definition and Components of ESM

- ESM quantifies mass-equivalent costs including mass, volume, power, cooling, and crew time for space systems.
- A metric used to compare applicable space technologies.
- Helps justify space-launch costs
- ESM does not include reliability, safety, and performance differences between trade study options.

Minimizing ESM for AI Systems

AI trash-sorting technology must be compact, energy-efficient, and low-maintenance to minimize ESM for space missions.

Balancing ESM with Performance

Design requires low ESM along with reliability, safety, and performance for mission success and sustainability.

$$ESM = M + (V*Veq) + (P*Peq)+ (C*Ceq)+ (CT*D*CTeq)$$

ESM	= the equivalent system mass value of the system of interest [kg]
M	= the total mass of the system [kg]
V	= the volume of system [m3]
Veq	= the mass equivalency factor for the volume [kg/m3]
P	= the power requirement of the system [kWe]
Peq	= the mass equivalency factor for the power generation [kg/kWe]
C	= the cooling requirement of the system [kWth]
Ceq	= the mass equivalency factor for cooling [kg/kWth]
CT	= the total crewtime requirement of the system[CM-Wy]
D	= the duration of the mission segment of interest [y]
CTeq	= the mass equivalency factor for the crewtime support [kg/CM-h]

AI TRASH SORTING TECHNOLOGIES

AI Vision

AI Image Recognition

To analyze visual data and identify different waste materials there are two free, open-source machine learning (ML) programs that have extensive use within the AI community. They are TensorFlow® and PyTorch®.

- These ML models have been used to create state-of-the-art object identification algorthims such as You Only Look Once (YOLO) or Real-Time Models for Object Detection (RTMDet)
- Advanced image recognition algorithms classify waste by color, shape, texture, and orientation for precise sorting.
- Hyperspectral cameras using an expanded wavelength spectrum are also used to capture images.
- Over 90% accuracy in waste item identification has been demonstrated
- Technical barriers still exist such as waste stacking on the sorting line, multiple objects coming into contact with each other, and objects with similar characteristics being mixed

Robotic Systems

Robotic Manipulators

Modern robotic arms use grasping, suction, and blowing to adapt to various waste sorting tasks.

Arms are often called manipulators due to the arm's ability to manipulate objects much like a human arm.

Commercially available robot arms with vision systems has grown rapidly. Some examples are Kinova® Inc. Gen3, FANUC Corp.'s LR Mate series, and Hiwonder® JetArm robots.

Two open source data sets of trash images, namely, TrashNet and Taco.

Inverse kinematic calculations determine the joint angles and motor positions required to place the grabber at a specific spatial coordinate to pick up an item.

- Becomes more challenging with a moving conveyor belt

Challenges in Space Environments

Dust and material degradation pose challenges to AI and robotic waste sorting in extraterrestrial settings.

Trash dispenser is designed for low gravity environments

- Uniform distribution of trash items on conveyor belt with minimal overlap

Conveyor system

- Does not need to be large, maybe 0.6m (2ft) to 0.9m (3ft) long, 0.3m (1 ft) wide
- Electric motor needs to be robust and reliable, sealed to prevent dust
- Rollers need to be jam-free

System should be capable of outside storage

AI Imaging System Table

COMPONENT	DESCRIPTION
Camera	Captures raw image data for digitization and analysis
Image Processing	Resizing, noise reduction, grayscale conversion, normalization
Detection Model	AI models like YOLO or RTMDet classify items in real time
Inverse Kinematics	Calculates robotic joint angles for accurate item pickup

IN-SPACE MANUFACTURING

Role of ISM and Recycling

In-Space Manufacturing Techniques

ISM uses additive manufacturing, welding, and machining to fabricate tools and components from local or recycled materials.

AI-Driven Recycling

AI waste-processing robots efficiently sort plastics, metals, and textiles into recycled feedstocks for ISM use.

Sustainable Mission Support

ISM combined with recycling reduces launch mass and enhances mission resilience through closed-loop material cycles.

Quality Assurance in ISM

Inspection and validation ensure reliability of manufactured components, supported indirectly by AI sorting purity.

CONCLUSION

Key Takeaways

Sustainable Deep-Space Habitation

AI-driven waste sorting is essential for sustainable living on Mars and the Moon by reducing waste and supporting recycling.

Technological Integration

Combining sensing, machine learning, and robotics enables reliable, long-term autonomous waste sorting.

Challenges and Innovations

Addressing dust, radiation, low ESM, and mechanical reliability challenges requires ongoing innovation based on terrestrial robotics advances.

Mission and Crew Benefits

Efficient waste sorting reduces mission costs, conserves payload mass, and reduces waste.