DEBRIS TO DELTA-V: LEVERAGING MAN-MADE SPACE RESOURCES FOR MOBILITY.

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Introduction: The Metal Propellant Ecosystem (MPE) represents an integrated Concept of Operations (conops) that addresses key challenges for space operators. The conops begins with the capture, transport, and transfer of resident space objects, or space debris. These objects are then salvaged and dismantled, with the susceptible parts melted down and processed into solid metal propellant. This propellant, aluminum in this feasibility study, is then distributed to end users for transfer into metal-propellant thrusters via swappable propellant cartridges. In a nutshell, MPE turns space debris into delta-v. This paper describes the results of a multi-faceted 2024 MPE feasibility study, which explored MPE elements from the design of the conops, goals and outcomes of prototyping, analysis of data gathered from using the prototypes in ground demonstrations in operational models, and exciting conclusions for quantifying the opportunity. Finally, opportunities for further innovation that arose from this program will be highlighted.

Method: Several avenues of work drove this feasibility study.

Prototyping. The latest prototype of the Space Foundry® was used to process simulated aluminum space debris into solid aluminum cylinders. These cylinders were then machined to include a central tungsten trigger pin, completing the formation of solid metal propellant prototypes for use in Neumann thrusters.

Experimentation. The performance of the prototyped solid metal propellant was tested on two Neumann thrusters in the propulsion laboratory at university partner Colorado State University. Performance measurements were gathered, and iterations were performed for data quality and thruster performance.

Analysis. Thruster specifications and performance data using the produced metal propellant were shared with industry partner Sierra Space for modeling of performance in station keeping of their space station concepts. Data and specifications were also shared with industry partner Astroscale US for modeling of application to their servicing spacecrafts. Their analyses were then conjoined into a larger economic analysis for commercialization implications. Risks were enumerated and analyzed.

Planning. A technology roadmap and heat map were developed to describe the development of the entire MPE capability from capture of resident space objects to distribution and refueling operations. Due to the complex nature of the conops, the multiple players in the value chain, and the technical challenges across the board, timelines were developed and execution risks enumerated. In addition, proof of concept missions were proposed that require only a small subset of the conops but would yield valuable information and economic benefit.

Findings:

Prototyping and Experimentation. Prototypes functioned and performed their appropriate roles successfully. Aluminum propellant was demonstrated to perform well and efficiently once the right boundary conditions were achieved.

Economic Benefits. Delta-v achieved through MPE has dramatically lower cost per unit of delta-v than other propellant architectures. There are three compounding factors that drive this outcome: (1) aluminum is orders of magnitude cheaper than other propellants even if purchased side-by-side on Earth, (2) aluminum sourced from space does not have launch cost because it is already in space, and (3) aluminum produces more delta-v per kilogram of mass than some other propellants. The analysis estimated that a provider of hydrazine would spend 250 times the amount of money that a provider of recycled metal propellant would spend to provide the same amount of delta-v to a customer in GEO. This stunning economic benefit in an emerging market for in-space refueling may represent a turning point in sustained space maneuver, or dynamic space operations.

Operational Benefits. It was also estimated that recycling only two defunct GEO satellites could provide enough metal propellant to provide all station-keeping for all GEO satellites for an entire year. One proposed mission of reduced scope involved recycling space station waste metal for use in station keeping of that same space station. This concept removes the need for debris capture, transport, and salvage, as well as distribution and refitting, because the entire conops would take place on the station itself with humans in the loop.

Estimates for volumes of space station waste metal, calibrated against actual waste metal volumes on the Internaional Space Station, suggest that recycling space station waste metal could meet more than half the need for the same station's station-keeping delta-v. MPE also reduces space debris by connecting it to markets for goods and services. MPE cleans up hazardous garbage, uses the garbage to beneficial effect, and delivers mobility more cheaply and efficiently than other propellants launched from Earth.

Risks. An analysis of risk was undertaken, finding four key categories of risk: (1) timing risk, indicating that the full concept of operations relies on multiple technologies and capabilities manifesting on the correct relative time frame, (2) technology risk, reflecting the challenges of the individual technological advancements, (3) policy risk, highlighting how each part of the value chain must be and (4) finance risk.

Implications and Opportunities: The economic and operational benefits of MPE have the potential to overcome the daunting risks facing its development and implementation. Companies should continue to work together to advance this important concept.