IAC-11.D1.2.1

INNOVATIVE TECHNOLOGIES FOR GLOBAL SPACE EXPLORATION

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Abstract

Under the direction of NASA's Exploration Systems Mission Directorate (ESMD), Directorate Integration Office (DIO), The Tauri Group with NASA's Technology Assessment and Integration Team (TAIT) completed several studies and white papers that identify novel technologies for human exploration. These studies provide technical inputs to space exploration roadmaps, identify potential organizations for exploration partnerships, and detail crosscutting technologies that may meet some of NASA's critical needs. These studies are supported by a relational database of more than 400 externally funded technologies relevant to current exploration challenges. The identified technologies can be integrated into existing and developing roadmaps to leverage external resources, thereby reducing the cost of space exploration. This approach to identifying potential spin-in technologies and partnerships could apply to other national space programs, as well as international and multi-government activities.

This paper highlights innovative technologies and potential partnerships from economic sectors that historically are less connected to space exploration. It includes breakthrough concepts that could have a significant impact on space exploration and discusses the role of breakthrough concepts in technology planning. Technologies and partnerships are from NASA's *Technology Horizons* and *Technology Frontiers* game-changing and breakthrough technology reports as well as the External Government Technology Dataset, briefly described in the paper. The paper highlights example novel technologies that could be spun-in from government and commercial sources, including virtual worlds, synthetic biology, and human augmentation. It will consider how these technologies can impact space exploration and will discuss ongoing activities for planning and preparing them.

I. INTRODUCTION

NASA recognizes that future mission success depends on advanced technologies that are now conceptualized or in development. The complex missions envisioned by the global space exploration community require a range of technologies outside the investment capability of a single national space agency. To support these missions despite constrained technology development budgets, NASA is attempting to find partnerships with other organizations and institutions that historically operate outside the space sector. As part of this effort, NASA's Exploration Systems Mission Directorate (ESMD), Directorate Integration Office (DIO) and The Tauri Group with NASA's Technology Assessment and Integration Team (TAIT) have completed several studies that identify novel technologies with potentially high payout for space exploration. These studies target partnerships by identifying organizations with technologies that align with human exploration applications. The studies are supported by a relational database of more than 400 externally funded technologies relevant to exploration challenges. The identified technologies provide opportunities for leveraging external resources, thereby reducing the cost of overcoming these challenges. The approach to identifying potential spin-in technologies and partnerships can apply to global space exploration efforts.

This paper highlights innovative technologies and potential partnerships across a range of economic sectors. It provides a brief overview of NASA's *Technology Horizons* and *Technology Frontiers* reports, which capture game-changing and breakthrough technologies for human exploration. It also discusses the External Government Technology Dataset and the white papers derived from this relational database. Identified technologies are linked to NASA's Space Technology Grand Challenges to highlight the potential for leveraging external technologies that provide solutions to significant space exploration challenges. Highlighted technologies include energy storage systems, efficient interplanetary propulsion, virtual worlds, human augmentation, and synthetic biology. Lastly, this paper provides a summary discussion of impacts from incorporating these technologies into global space exploration strategies.

II. Overcoming the Challenges of Spaceflight

NASA and other national space agencies are planning complex, challenging exploration missions that will push the boundaries of human capability and understanding. Ambitious, long-duration human missions to Near Earth Asteroids and onto Mars are targets for the next generation of explorers. Robotic missions to these destinations and throughout our solar system will increase scientific knowledge in this generation and pave the way for the next. However, significant technical challenges must be overcome to enable future exploration. These challenges are exemplified in NASA's Space Technology Grand Challenges, a set of 13 technical challenges that are key elements to expanding human presence in space, managing resources, and enabling scientific discovery. NASA is currently seeking technical solutions to these changes through considerable investment in internal research and development and external partnerships.

External partnerships are a key element of NASA's strategy to meet these challenges. With a future of constrained national budgets, NASA cannot solely rely on in-house development to meet the challenges for global space exploration. Partnerships with other national space agencies provide opportunities to leverage strengths across spacefaring nations. A second and equally important source of external partnerships is government, academic, and commercial institutions that traditionally operate outside the space sector but are developing crosscutting technologies that apply to exploration challenges. NASA is currently developing and using tools and processes that identify cost-saving partnerships from outside the space industry.

III. NASA's Approach to Technology Partnerships

NASA vigorously participates in partnership opportunities with other government agencies, industry, and academia. Partnerships afford NASA the opportunity to leverage advancements made by other organizations, to build strong relationships with other technically minded organizations, maintain connection with cutting-edge development, and monitor technical advancements that can benefit NASA missions and objectives. Specifically, the Human

Exploration and Operations Mission Directorate (HEOMD) is interested in technologies that would enable human spaceflight. To that end, the Systems Analysis and Integration Division (SAID) of HEOMD has developed processes and tools for identifying organizations outside of NASA that are developing capabilities and technologies synergistic to those needed to enable human spaceflight.

The Technology Assessment and Integration Team (TAIT) at NASA Langley Research Center, along with TAIT team members from The Tauri Group, have supported these activities. The process and tools that TAIT has developed include numerous technology development trending reports and relational databases used to facilitate communication of research findings. The technology reports include focused technology white papers, the *Technology Horizons: Game-Changing Technologies for the Lunar Architecture* report (focus on identifying near-term technologies set to mature within the next 10-20 years), and the *Technology Frontiers: Breakthrough Capabilities for Space Exploration* report (focus on long-term technology areas that could mitigate significant challenges and change the paradigm of space exploration). Additional research and relational database communication include External Government Technologies (EGT) Datasets. These datasets describe a variety of other organizations developing potentially synergistic technologies and how those advancements could relate to specific human spaceflight objectives and goals. The reports and databases have been used extensively to identify partners, initiate partnership activities, and build relationships with these organizations.

IV. EGT: an Integrated Technology Tracking Tool and Supporting White Papers

The External Government Technologies (EGT) data set, part of the relational database MATCH (Matching Applicable Technology to exploration Challenges), is a technology tracking tool that identifies technologies and programs relevant to space exploration funded by U.S. government agencies, excluding NASA. EGT includes more than 400 externally funded, innovative technologies and over 800 technology development programs. Programs are identified in the Department of Defense (DoD), Department of Energy (DOE), Department of Homeland Security (DHS), Department of Commerce, and other technology development departments and agencies. The Tauri Group and TAIT first developed the EGT dataset in 2004, and EGT has supported NASA’s technology tracking and partnership identification activities ever since.

As a key element of the MATCH relational database, the EGT dataset is a searchable, easy-to-access, and integrated tool that provides concise information on novel technologies and potential partnership opportunities. EGT is composed of a collection of technology records that include clear and succinct descriptions of the technology, its intended application, its potential application for space exploration, key performance metrics, technology readiness level (TRL) assessment, funding profile, organizations and universities involved in technology development, and contact information for potential partners. The data within EGT is organized around technology to enable quick linking between NASA needs and external development. Government technology development projects are tied to each technology record and provide sufficient information to indicate development efforts and support partnership. EGT is not an exhaustive catalog of all government technology development efforts; rather, it provides a better understanding of trends within national technology development efforts.

The EGT dataset is the primary data source for a series of white papers and reports that characterize the types and range of space-relevant research activities organized around a specific exploration mission or challenge. White paper topics include energy storage, cryogenic propellant transfer and storage, electric roving vehicles, and robotic systems. These reports provide additional information on technology development in these sectors and link external technologies to NASA activities. Table 1 provides examples of technologies from the EGT dataset and related white papers:

Technology Name	Description
3-D Printing	Additive manufacture techniques that build products layer-by-layer rather than milling from solid feedstock.

Autonomous Mesoscale Robotic Ground Vehicles	Autonomous miniaturized robots that range in size from 50cm to 1cm and a few kilograms to a few grams.
Silicon Nanowire Lithium-Ion Battery	A lithium-ion battery with a nanostructured silicon anode.
Composite Hub Flywheel Energy Storage System	A flywheel system that uses new materials to enable higher rotational speeds resulting in a higher energy storage capacity.
Soft Surface Antibacterial Polymer	Biocompatible polymer coatings that decrease the ability of bacterial organisms to establish themselves and create biofilms.
Superconducting Magnetic Energy Storage	Superconducting magnetic energy storage systems, which provide very efficient, quick charge/discharge energy storage.
Synthetic-Bio Robot	An autonomous robot resulting from the fusion of synthetic biology, electronics, and cybernetics.

Table 1: EGT example technologies

V. Technology Horizons and Technology Frontiers

The *Technology Horizons* and the *Technology Frontiers* reports, developed by NASA and The Tauri Group, are designed to increase awareness of technology trends that may impact future exploration missions and identify organizations driving those trends. The *Technology Horizons: Game-Changing Technologies for the Lunar Architecture* and the *Technology Frontiers: Breakthrough Capabilities for Space Exploration* reports look across the economy to identify these trends, providing an alternative to the internally focused vision of technology development common to research and development organizations.

The first report in this series, *Technology Horizons*, focuses on near-term technology areas—technologies likely to be available within the next 10-20 years—that benefit from a broad research community, across the economy. These technology areas, identified as “game-changing,” could have substantial impact, including dramatic performance improvements, on multiple systems for exploration. Many of the potential game-changing technology areas are considered important research thrusts in sectors typically external to the space community, providing partnership opportunities.

Published in 2009, the *Technology Horizons* report includes 19 technology areas that group 110 technology concepts. The report also identified a technology watch list of top technology areas likely to see significant advancements and research investment without NASA participation. Example technology areas include:

Technology Area	**Description**
Advanced Nanotube-Based Materials	Materials enabled by nanotechnology to provide strong, lightweight aerospace structures.
High-Energy Density Matter Cryogenic Solids	Solidified high-energy propellants that are normally a gas or liquid at room temperature.
Advanced Cryogenic Technologies	Advanced cryogenic storage and cryocooler technologies that enable propellant depots, long-duration interplanetary missions, and volume- and mass-savings.
Anti-Radiation Drugs	Pharmaceuticals that prevent or repair damage from ionizing radiation.
Emerging Communications Systems	Communication systems that significantly increase bandwidth for interplanetary and mission site links.
Massive Online Collaborative Environments	Technologies for organizing, presenting, and connecting data to create an immersive collaborative environment.

Table 2: *Technology Horizons* example technology areas

The *Technology Frontiers* report has similar goals as the *Technology Horizons* report, and identifies areas of promising technology advancement. However, *Technology Frontiers* targets less mature technologies, specifically breakthrough concepts that may mature within 40 years. As a future-thinking document, the *Technology Frontiers* report identifies high-risk technologies that could change the paradigm for human space exploration. Breakthrough concepts identified in the report are organized by broad capabilities that closely align with NASA's Space Technology Grand Challenges and represent some of the largest challenges to space exploration. Each breakthrough capability sketches out the technological achievements required to overcome these challenges and can include numerous individual technologies. The report also identifies organizations currently researching preliminary technologies that may lead to breakthrough capabilities, allowing space exploration organizations to plan for future developments and encourage novel, long-term partnerships that may lead to innovative solutions to global exploration challenges.

Published in 2010, the *Technology Frontiers* report identifies 13 breakthrough capabilities, 9 crosscutting capabilities, and nearly a hundred technology concepts that may be the focus of future technology partnerships. Some example breakthrough capabilities and technology concepts include:

Breakthrough Capability	Technology Concept	Description
Seamless Human-Computer Interaction: Technologies and tools for removing barriers to communication between humans and computers.	Brain Machine Interface (BMI)	Neural interfaces for controlling equipment external to the user.
	Simulated Reality	Beyond virtual reality, providing a seamless environment.
Space Oasis: Way stations for resupply, service, assembly, and maintenance on orbit	Autonomous Robotic Assembly	Using robots to construct large complex structures in space.
Go-Anywhere Roving: Vehicles for transportation on planetary bodies allowing unconstrained exploration on, over, and under the surface	Flapping-Wing Rovers	A biologically derived solution for powered flight.
Efficient Interplanetary Travel: Lightweight, highly maneuverable, and rapid transportation to and around locations in space	Nuclear Pulse Propulsion	A series of supercritical, explosive events that provide energy or momentum.
Super Humans: Technologies that improve human performance beyond Earth-norm.	Anti-Aging	Technologies that stop or reverse the effects of aging.
	Physical Interfaces	Artificial components that increase performance.

Table 3: *Technology Frontiers* breakthrough capabilities and technology concepts

The technologies identified in the EGT dataset, *Technology Horizons* report, and *Technology Frontiers* report are novel technologies identified across a wide range of economic sectors. Although the sectors are not necessarily linked to space exploration, the identified technologies have crosscutting applications and could significantly impact future exploration capabilities. A comparison between identified technologies and NASA's Space Technology Grand Challenges shows the potential for leveraging external technologies to meet some of the largest challenges to space exploration.

VI. Highlighted Technologies

According to NASA, the Space Technology Grand Challenges guide discussion and innovation leading to technology solutions that solve current exploration challenges, radically improve capabilities, or deliver entirely new capabilities that enable future missions. They are centered on three themes: expanding human presence, managing in-space resources, and enabling transformation exploration and scientific discovery. The thirteen grand challenges are Economical Space Access, Space Health and Medicine, Telepresence in Space, Space Colonization, Affordable Abundant Power, Space Way Station, Space Debris Hazard Mitigation, Near-Earth Object Detection and Mitigation, Efficient In-Space Transportation, High-Mass Planetary Surface Access, All Access Mobility, Surviving Extreme Space Environments, and New Tools of Discovery.

The technologies highlighted below are organized by Space Technology Grand Challenges. We selected Economical Space Access, Space Health and Medicine, Telepresence in Space, Affordable Abundant Power, Space Way Station, Efficient In-Space Transportation, and All Access Mobility to illustrate the range of challenges that may be addressed by leveraging external technologies and partnerships.

Economical Space Access

Launching exploration missions with current technology and methods is cost-prohibitive for frequent and robust human and robotic exploration of space. Estimates suggest mission cost must be reduced by an order of magnitude to enable the ambitious goals of global space exploration. Advanced nanotube-based materials and high-energy density matter cryogenic solids may help contribute to the goal of economical, reliable, and safe access to space. .

Advanced Nanotube-Based Materials

Nanotubes are long, thin, atomic scale cylinders, either exclusively carbon atoms or of boron and nitrogen. Their nanostructure can have a length-to-diameter ratio as large as 28,000,000:1, unequalled by any other materials. These cylindrical molecules are extraordinarily strong and have a broad range of electronic, thermal, and structural properties that change depending on the nanotube. Novel properties make them potentially useful in many applications in nanotechnology, electronics, optics, and other fields of materials science, as well as potential uses in architectural fields.

Nanotube-based materials offer a lightweight alternative to traditional aerospace structures, including fairings, propellant tanks, and engine nozzles. By significantly reducing the weight of launch vehicles, advanced nanotube-based materials can reduce launch costs. Both academic and commercial organizations have studied or produced nanotube-based materials, including The Australian National University and Nanocomp Technologies. Potentially these materials may result in reusable, single-stage-to-orbit vehicles, resulting in a dramatic reduction in launch costs, potentially the order of magnitude necessary to meet the Economical Space Access grand challenge.

High-Energy Density Matter Cryogenic Solids

Cryogenic solid propulsion systems freeze propellants to improve performance. Solid propellants tend to be denser than their liquid counterparts and consequently require less volume. They can include energetic additives, also known as high-energy density matter (HEDM), that significantly increase specific impulse. For example, lithium boride mixed with solid hydrogen or ozone mixed with solid oxygen can increase specific impulse by 107 and 25 seconds, respectively. Motors that use cryogenic solid propellants tend to be less complex than liquid engines, reducing technical risk. Cryogenic fuels and oxidizers include water, hydrogen peroxide, polymeric materials (such as polyethylene), aluminum, hydrocarbons, solid oxygen, and solid hydrogen. This technology is in an early stage of development and with potential applications for improving launch performance, thereby supporting Economical Access to Space.

Space Health and Medicine

The space environment is hostile to human life. Current technologies protect astronauts for limited durations within the protective shield of the Earth's magnetosphere. Zero gravity, radiation, increased disease virulence, and physiological effects of cramped space environments contribute to risks that currently prevent long-duration space exploration. New technologies are necessary to meet this challenge and enable future missions. Soft surface antibacterial polymer, anti-radiation drugs, and technologies that allow humans to exceed their physical limitations provide potential solutions to remove, mitigate, or engineer around these risks.

Soft Surface Antibacterial Polymer

Biocompatible polymer coatings create a softer surface on solid objects, decreasing the ability of bacterial organisms to establish themselves and create biofilms. (Biofilms are adhesive, antibiotic-resistant films created by bacterial colonies. Once established, it is difficult for antibiotics to remove or penetrate the film and kill the underlying bacteria.) Biocompatible coatings take advantage of a recent finding that bacteria prefer firm surfaces to soft ones. Biocompatible coatings create a softer surface feature, making it more difficult for bacteria to coat a surface area and establish themselves. Biocompatible coatings are composed of 50-nanometer thick polyelectrolyte (a charged polymer), with alternating layers of different acidity levels. When hydrated with a near-neutral liquid, like water, these polymers soften the stiffness of the material.

When applied to habitat or life support systems, these coatings can increase the safety of the crew by minimizing the growth of bacteria and other harmful microbes on the systems. The ventilation and water system, in particular, could benefit from these coatings. Potential partners include researchers from the Massachusetts Institute of Technology (MIT), who studied these coatings with funding from the National Science Foundation (NSF).

Anti-Radiation Drugs

This technology area includes pharmaceutical drugs that counteract the toxic effects of exposure to radiation. Existing anti-radiation drugs can act as anti-oxidants or help to regulate cellular processes that radiation may disrupt. Emerging techniques include immunization against the classes of toxins radiation releases in the body. Another technique is to administer heat shock proteins—one of the body's natural responses to environmental stressors. Protecting astronauts from galactic cosmic radiation exposure is a major challenge for long-duration space missions. The very high amounts of mass required to bring radiation exposure down to safe levels could be traded against the use of pharmaceutical solutions that bring health risk down to acceptable levels.

Technology concepts in this area include:

- Genomic-based Anti-radiation Drugs and Protocols
- Heat Shock Proteins
- Nanotube Anti-radiation Pill
- Radiation Vaccine

In the U.S., anti-radiation drugs have been studied by the Armed Forces Radiobiological Institute. South Korea and Russia have also investigated heat shock proteins and radiation vaccines, respectively.

Super Humans

Techniques and technologies expand the limits of human capabilities; reducing the need for sleep, increasing alertness, and mitigating stress. Unlike other technologies that support the Space Health and Medicine grand challenges, technology concepts in this breakthrough area engineer the human, increasing crew capabilities and enabling safe exploration of environments hostile to non-engineered humans. Example technology concepts include:

Anti-Aging: Includes a number of different, related concepts that would be combined to overcome the aging process. Research shows that there may be a genetic component to aging, and it may be possible to switch off the genes that cause a kind of planned obsolescence in the human body. Anti-aging is a multidisciplinary and crosscutting application, with a number of different approaches to extending human life and increasing performance. Anti-aging technologies could enable extremely-long-duration missions and may remove some of the risk associated with space radiation and zero-g adaptations like atrophy and bone loss. University of South Florida, Indiana University, Tufts University, and Leiden University in Holland have all studied anti-aging technologies.

Physical Interfaces: Includes physical and neural interfaces that augment human capabilities, such as exo-skeletons and infrared vision. Exo-skeletons increase and amplify the amount of force applied by the human operator. They could increase astronauts' strength and range on EVA and compensate for bone and muscle degeneration in microgravity. Neural infrared vision interfaces hard-wire visual sensing capabilities directly into the nervous system. The ability to see in different parts of the spectrum could be valuable for space operations, including navigation, exploration, and science operations. Physical interfaces have been studied in U.S. and international universities, including MIT, University of California Berkeley, and University of Cambridge. It has also been a subject of interest at the Defense Advanced Research Projects Agency (DARPA).

Telepresence in Space

Providing access to an exploration destination for humans is a costly and risky endeavor. As such, space exploration has been limited to a small pool of highly specialized participants. Through advances in telepresence, exploration destinations can be brought to a wide range of explorers, vastly increasing participation and scientific output. Through seamless, intuitive virtual environments, individuals on Earth, or in orbit around another planet, can explore our solar system. Emerging communications systems, massive online collaborative environments, and seamless human-computer interaction technologies help transmit, display, and provide interfaces to tele-exploration environments.

Emerging Communications Systems

Emerging communications systems provide increased bandwidth and throughput for data between systems as well as from a lunar or planetary surface to Earth. Optical crosslinks or signals can increase data rates to satellites or in a local area network. X-ray communications could provide high data rates while penetrating radio frequency interference from shielding or plasmas generated during reentry. New advanced communication systems are necessary to transmit extensive data, enabling real-time, interactive exploration.

Technology concepts in this area include:

- Optical Crosslinks, Uplinks, and Downlinks
- Optical Wireless Communications Onboard the Spacecraft
- X-ray Communications

Research in these technologies is ongoing in U.S. government organizations such as the Department of Defense (DoD) and within international space agencies such as the European Space Agency (ESA).

Massive Online Collaborative Environments

This category describes ways of organizing, presenting, and connecting data to create an immersive collaborative environment. The most popular example of this type of environment is mirror worlds. Mirror worlds is a proposed interface and structure for a global information network of the near future. Mirror worlds represents a virtual, dynamic, four-dimensional world accessible through a computer, where structures represent data sources that may or may not have a physical counterpart in the real world. Mirror worlds goes beyond the notion of virtual worlds, foreseeing the existence of advanced optical networks that allow people to share real spaces and real data. Such systems represent the next model for collaboration and decision-making in a distributed environment, a key component of future exploration through telepresence.

Technology concepts in this area include:

- AlloSphere
- Digital Swarming
- Mirror Worlds

Cisco Systems is a major commercial developer of massive online collaborative environments.

Seamless Human-Computer Interaction

Human-computer interfaces enable humans to view data and control machinery in seamless and intuitive ways. Astronauts, mission control personnel, and the public enjoy immediate access to data to inform decision-making processes. Complex tasks are negotiated with ease, and vast amounts of data are processed and digested rapidly. Technologies that enable seamless human-computer interaction will be a key component of telepresent and virtual exploration. Example technology concepts include:

Brain Machine Interface (BMI): Also known as brain-computer or neural interface, this interface monitors the user's neurons and interprets his or her signals. This provides hands-free control of machinery and software and access to information. This technology has allowed amputees to do tasks such as controlling robotic limbs, driving motorized wheelchairs, and typing using only their minds. BMI interfaces are unique in that their operation is independent of the user's physical ability. They have no manual component and therefore could be a very useful technology in space environments, where manual interfaces can be difficult to operate due to factors such as microgravity or bulky suits. BMI technologies represent one avenue to life-like exploration of digitized replicas of exploration destinations. Organizations researching or developing BMI include DARPA, University of Florida, Honda Research Institute, and CyberKinetics.

Simulated Reality: Moves a step beyond virtual reality by creating a reality that is indistinguishable from real experiences. Theoretically, this simulated reality would be so completely immersive that the user would be unaware that he or she was using a simulated reality interface. The technologies that could achieve this state would work directly on the brain itself, blocking real sensory input and replacing it with simulated input on the level of individual neurons. Simulated reality has been studied by researchers at Arizona State University and Stanford University.

Affordable Abundant Power

Current power system technologies limit human and robotics exploration capabilities. Light-weight, safe, and affordable power systems that do not degrade over useful lifetimes are necessary for future long-duration exploration missions. This grand challenge focuses on providing abundant, reliable, and affordable power to all classes of exploration missions. Silicon nanowire lithium-ion batteries, composite hub flywheels, and superconducting magnetic energy storage systems are technologies that help meet this challenge.

Silicon Nanowire Lithium-Ion Battery

The electrical storage capacity of lithium-ion batteries is limited by how much lithium can be held in the battery's anode, which is typically made of carbon. Although silicon has a higher capacity than carbon, it swells upon charging and then shrinks during use. This expand/shrink cycle typically degrades the performance of the battery, unless it uses a nanostructure, which has silicon regions and voids or contraction regions. While one layer expands, the other contracts, producing a net effect of zero expansion. The lithium is stored in a forest of tiny silicon nanowires, each with a diameter one-thousandth the thickness of a sheet of paper. The nanowires inflate four times their normal size as they soak up the lithium. The nanostructures provide greater total surface area, improving lithium uptake.

The U. S. Army is interested in silicon nanowire lithium-ion battery chemistries for higher energy capacity and longer cycle rechargeable batteries for dismounted soldiers. For extraterrestrial use, silicon nanowire lithium-ion batteries could replace current batteries in robotics, planetary surface vehicles, space infrastructure, and mobile devices, significantly increasing performance.

Composite Hub Flywheel Energy Storage System

The composite hub flywheel energy storage system is a composite hub that supports an optimized high-speed composite rim. This system is made of carbon and fiberglass that can withstand high speeds of rotation (up to 22,500 revolutions per minute). To maintain this speed, a vacuum system is used to reduce air resistance and friction. A high-speed magnetic lift system virtually eliminates friction and allows for long, maintenance-free operation.

Unlike batteries that degrade at temperature extremes, flywheels sustain energy output and long-term life spans in harsher climates, potentially including environments found at exploration destinations. Potential partners include Beacon Power Corporation, whose projects have been funded by both the Department of Energy (DOE) and the California Energy Commission.

Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) systems store energy in magnetic fields created by direct current in a coil of superconducting material. SMES can store several megawatts of power; research is being conducted on SMES with 100 megawatt capacities. One- to two-megawatt systems are commercially available with energy densities of approximately 0.3kWh. SMES systems require immersion in cryogenic fluids to maintain the superconducting properties of the coil. Advances in high-temperature superconductors could make this technology more cost-effective.

NASA could use SMES systems as a component of permanent exploration infrastructure power management and distribution systems. Specifically, these systems could be used to provide power if a large spike in power demand occurs. The presence of ultra-cold, permanently shadowed craters on some exploration destinations could reduce the need for active cryogenic cooling. The U.S. Navy and the NSF have funded work on SMES at the Missouri University of Science and Technology.

Space Way Station

Pre-positioning consumables and providing infrastructure for constructing, fueling, and repairing spacecraft could support frequent and sustainable exploration. The Space Way Station grand challenge seeks to develop technologies for pre-deploying in-situ resources and enabling in-space manufacturing, storage, and repair. Autonomous robotic assembly and 3-D printing are two technologies that help solve this challenge.

Space Oasis

Servicing and assembly stations in space are available for routine, autonomous refueling, assembly, and robotic maintenance of spacecraft. Stations range from small mobile refueling stations to monolithic concepts capable of performing complex servicing and assembly tasks and even supporting crew accommodations. Spacecraft can autonomously dock to the station to be serviced. Autonomous maintenance robots are reliable and readily available to inspect and repair spacecraft as needed. Stations provide upgrades to spacecraft, such as telescopes, with new and improved parts and instruments. Finally, some stations can provide in-orbit assembly of large space structures. These structures arrive at the station in separate cargo containers to be robotically unloaded and assembled. Example technology concepts include:

> *Autonomous Robotic Assembly:* Autonomous robotic assembly is the process of using robots of varying degrees of intelligence to construct large complex structures in space without human intervention. Robotic assembly could enable construction of solar power satellites, large communications arrays, modular spacecraft for long-range travel, and science structures, such as large telescopes. The advantages of on-orbit assembly include inherent serviceability and expandability, launch packing efficiency, smaller launch units, structural efficiency, the ability to build very large structures, and that the complexity of a structure does not have to increase when its size increases. The Carnegie Mellon University Robotics Institute, University of Southern California Information Science Institute, and the Vienna University of Technology have all conducted research on autonomous assembly robots.

3-D Printing

3-D printing technologies manufacture solid objects directly from computer modeling files, such as computer assisted design (CAD) files with additive manufacturing techniques. Multiple production processes enable printing of prototype components or complete operational devices using various feedstocks (the production material) supplied as a powder or extrudable fluid. The types of materials that can be used for 3-D printing are limited, but recent breakthroughs enable steel and titanium feedstock, and other advanced materials may be possible. Another advance in 3-D printing is the use of inkjet technologies to print conductive substances, enabling manufacture of circuit boards or other integrated circuits.

3-D printing was designed for terrestrial rapid prototyping but could enable space way stations to manufacture unique components or systems in situ, including spare parts or components to construct spacecraft. Mission support teams could quickly develop a new component and "ship" it to the way station as digital blueprints, reducing the time and cost necessary for launching replacements. 3-D printing is versatile and can support the manufacturing of products such as fuel tanks or satellite plating. The Office of Naval Research, MIT, and Cornell University have researched and developed 3-D printing technologies.

Efficient In-Space Transportation

Propulsion system efficiency is a key challenge to transporting high-mass robotic and human exploration systems throughout space. Time in transit also has to be minimized for human missions. This grand challenge focuses on technologies that provide rapid, efficient, and affordable transportation through space, such as advanced cryogenic technologies and nuclear pulse propulsion.

Advanced Cryogenic Technologies

Advanced cryogenic fuel management technologies have the capability to greatly enhance crewed and robotic space missions. In-orbit fuel transfer systems enable the use of propellant depots in low Earth orbit, which would allow for architectures that greatly increase the amount of mass landed on the Moon or larger structures in orbit. Advanced cryogenic storage and cryocooler technologies not only enable the use of propellant depots but also the use of cryogenic propellants on long-duration interplanetary missions. The lower mass and volume of cryogenic propellants allows a higher amount of spacecraft mass and volume devoted to payloads. This may be critical for missions like Mars sample returns. Propellant depots and long-term fuel storage, which have been researched by DARPA, Orbital Technologies Corporation, and the United Launch Alliance (ULA), may be critical to a deep space transportation network supporting Efficient In-Space Transportation.

Nuclear Pulse Propulsion

Nuclear pulse provides a different technical approach to nuclear propulsion. Instead of a stable reactor providing energy for a rocket, a series of supercritical, explosive events provide energy or momentum. A variant of nuclear pulse propulsion that mitigates some of the engineering challenges and may eliminate the social and political hurdles is micro-fusion pulse propulsion. This concept uses micro-fusion pulses to potentially enable a breakthrough interplanetary nuclear pulse propulsion system.

Micro-fusion pulse propulsion relies on small pellets of fusion fuel, ignited within a rocket combustion chamber. A common design proposed for these pellets includes fusion fuel surrounded by a hard metal casing. Deuterium and tritium are considered as fuel sources; low-neutron fuels are also possible albeit more challenging. High-power lasers or antiproton beams ignite the fuel through a pinhole in the casing. Antiproton beams are particularly attractive, since they eliminate the need for massive optics and high-powered laser sources. In the case of the antiproton beam, a subcritical fission target reacts with the antiprotons and produces high-energy fission products that ignite the fusion fuel. The energy from these reactions could heat a propellant or provide thrust through magnetic confinement and a magnetic nozzle. With a magnetic nozzle, Isp of 100,000 seconds is possible, and system thrust is dependent on the rate of explosions (35,000N for 10 pulses per second). Lawrence Livermore National Laboratory is investigating this concept for terrestrial power applications. Other potential partners in development or research of this technology include the DOE, Pennsylvania State University, and University of Michigan.

All Access Mobility

Current mobility technologies limit exploration of moons, asteroids, and planetary bodies with different environments and gravities than Earth. Mobility systems designed for space travel require detailed planning, and most are designed only for exploration destinations with fairly high partial gravity. This grand challenge focuses on technologies that enable mobility on, over, or under any destination. Technologies that could support All Access Mobility include flapping-wing rovers, autonomous mesoscale robots, and synthetic-bio robots.

Flapping-Wing Rovers

Flapping-wing atmospheric rovers are a biologically derived solution for powered flight. Like the SmartBird recently featured on TED, these rovers use flapping wings instead of airflow over an airfoil to provide lift. These systems can take advantage of leading edge vortices generated by the flapping wing to increase lift and improve aircraft performance. This approach could be particularly useful for planetary environments with low-density atmospheres, where fixed-wing and rotorcraft are not practical, and could provide atmospheric mobility with low translational velocities. Systems can be designed with alternating sets of flapping wings to reduce or eliminate oscillating motion on the fuselage and payloads. Power systems for proposed flapping-wing rovers include chemical energy conversion systems for mechanical energy and electricity to power payloads. These rovers can be scaled for different atmospheres and missions to provide flexible aerial mobility. This technology has been of interest to government, academic, and commercial organizations, including DARPA Defense Sciences Office, Stanford University, and AeroVironment, Inc.

Autonomous Mesoscale Robotic Ground Vehicles

Autonomous mesoscale robotic ground vehicles are small (~50 cm to ~1 cm), lightweight (few kg to 1g), and low-cost robotic sensor platforms with surface locomotion capabilities. Currently, there are several independent and collaborative efforts to develop mesoscale ground vehicles. These ground vehicles are designed to work in swarms; traverse rough terrain or vertical walls; access confined, dark, and GPS-denied locations; and provide useful, real-time information on inaccessible or dangerous environments. Although the sensors on these robotic vehicles are limited by payload capacity and power, these systems can work as a networked swarm to provide sophisticated and detailed information about an environment, including mapping, traverse planning, target identification, and search and rescue. Current development of mesoscale robotic ground vehicles covers a range of vehicle sizes and locomotion capabilities. For larger vehicles (>3g), DC motors are commonly used with mobility gates of crawling or climbing. For very small vehicles (<3g), novel mobility mechanisms like piezoelectric and shape memory alloy wire actuators are possible. These smaller systems tend to crawl at slower speeds, but they can access crevices and holes of a few centimeters and survive long falls. Future systems may have more advanced locomotion options like jumping, gliding, or burrowing.

The DoD is developing autonomous mesoscale robotic vehicles to provide intelligence information on locations denied to people or larger robots, but numerous space exploration applications also exist. A space mission could use swarms of autonomous mesoscale robots to characterize an exploration site, identify sites of scientific interest, map terrain and plan traverses, and supplement data from other rovers.

Synthetic-Bio Robot

This technology builds on the emerging field of synthetic biology by using the principles of biomimicry to develop a micro-scale cyborg. The current design for the synthetic-bio robot includes electronic and engineered biological components in an integrated autonomous system. The micro-scale robot is designed to look like and mimic a sea lamprey. Synthetic mammalian muscle cells generate undulatory movement, while genetically modified yeast cells act as chemical sensors. These cells are simplified by suppressing or enhancing select gene responses to enable a simple input/output interface. Additional visual receptors are encoded in the biological cells to enable sensation and actuation through light signals. Signals are processed and transmitted by an electronic nervous system and brain. The cells use stored glucose, converted to ATP by mitochondria, for energy, and the electronic components are powered by a microbial fuel cell.

Synthetic-bio robots like Cyberplasm could explore planetary bodies. These robots could be programmed to seek out specific materials or chemical compositions and signal if a threshold level is discovered. Currently, the Cyberplasm project, a collaboration of four universities, is expected to detect preprogrammed chemicals and swim toward the sources.

VII. Summary

As exemplified in the Space Technology Grand Challenges, global space exploration efforts face significant technical challenges to human and robotic exploration. Tools like EGT, *Technology Horizons*, and *Technology Frontiers* that identify relevant technologies developed outside the space community represent an economical approach to overcoming these challenges.

This paper highlights several technologies and concepts under development that meet national and economic needs and also closely align with NASA's Space Technology Grand Challenges. The linking between external technologies and exploration challenges, showcased above, illustrates the potential of leveraging externally funded technologies and partnership to acquire or cooperatively develop technical solutions. NASA is already leveraging the tools identified in this paper to promote successful partnerships and provide a cost-effective solution to the challenges of space exploration.