INNOVATIVE TECHNOLOGIES FOR HUMAN EXPLORATION: OPPORTUNITIES FOR PARTNERSHIPS AND LEVERAGING NOVEL TECHNOLOGIES EXTERNAL TO NASA

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Abstract

Human spaceflight organizations have ambitious goals for expanding human presence throughout the solar system. To meet these goals, spaceflight organizations have to overcome complex technical challenges for human missions to Mars, Near Earth Asteroids, and other distant celestial bodies. Resolving these challenges requires considerable resources and technological innovations, such as advancements in human health and countermeasures for space environments; self-sustaining habitats; advanced power and propulsion systems; and information technologies. Today, government space agencies seek cooperative endeavors to reduce cost burdens, improve human exploration capabilities, and foster knowledge sharing among human spaceflight organizations. This paper looks at potential opportunities for partnerships and spin-ins from economic sectors outside the space industry. It highlights innovative technologies and breakthrough concepts that could have significant impacts on space exploration and identifies organizations throughout the broader economy that specialize in these technologies.

Introduction

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) have completed several studies that identify novel technologies with potentially high payout for human exploration. These studies sought to identify potential organizations for partnerships, including organizations that NASA has not collaborated with but have technologies with potential human exploration applications. The task of gathering technology intelligence is supported by a constantly updated relational database of more than 400 externally funded technologies that are relevant to current exploration challenges. The identified technologies provide opportunities for leveraging external resources and identifying partners to meet exploration challenges, thereby reducing the cost of overcoming these challenges. The approach to identifying potential spin-in technologies and partnerships could apply to other national space programs and international, multi-government activities.

This paper provides a brief overview of NASA's *Technology Horizons* and *Technology Frontiers* reports and the External Government Technology Dataset. This paper also highlights novel technologies drawn from these sources that could significantly impact space exploration capabilities and be infused from government and commercial sources into space exploration programs. Identified key technology areas include virtual worlds, human augmentation, synthetic biology, and novel computing architectures. Lastly, this paper provides a summary discussion of the impacts these technologies may have on enabling space exploration, and it explores the benefits of collaborating with commercial, government, and academic organizations to infuse innovative capabilities into exploration architectures.

Overcoming the Challenges of Spaceflight

Human spaceflight organizations have ambitious goals for expanding human presence throughout the solar system. NASA, as well as other national space agencies, is considering a complex set of potential exploration missions, such as long-duration missions to Mars, the Moon, or Near Earth Asteroids. Although the destinations and means for these future missions have not been finalized, NASA has invested considerable research and development to understand the requirements for and challenges of long-duration human exploration beyond Earth orbit.

Space-faring nations have invested in a wide range of technologies for human spaceflight, but currently national space exploration organizations remain far from the goal of extending human exploration. A sizable fraction of global space exploration budgets over the next several years is still required to develop the suite of tools and technologies necessary for exploration missions to the proposed destinations. In an era of diminishing national budgets, in-house development may represent the slowest and least efficient method of procuring these technologies. Alternatively, space exploration organizations can, and are beginning to, leverage new tools and processes that identify cost-saving partnerships for novel technologies from economic sectors outside the space industry.

Although NASA develops many technologies for specific exploration systems, many crosscutting technologies—technologies developed for multiple systems or that cross economic sectors—can benefit human space exploration. By leveraging external research on crosscutting technologies to the maximum extent possible, NASA can focus technology development resources on NASA-specific technologies. Anti-radiation pharmaceuticals, lightweight ballistic armor, universal power and data adaptors, and advanced computing systems are examples of crosscutting technologies that could have significant impacts on future exploration missions and are developed by commercial and non-space-related government research programs. Tools that help NASA identify crosscutting technologies and potential partnership opportunities are described below.

EGT: an Integrated Technology Tracking Tool

The Tauri Group and NASA's Technology Assessment and Integration Team at Langley Research Center have developed a technology tracking tool that identifies technologies and programs relevant to space exploration and funded across the U.S. government. The External Government Technologies (EGT) data set, part of the relational database MATCH (Matching Applicable Technology to exploration Challenges), monitors and catalogs more than 400 externally funded, innovative technologies and over 800 technology development programs in other government agencies (including Department of Defense (DoD), Department of Energy (DOE), and Department of Homeland Security (DHS)) that could be leveraged for space exploration. Since its development in 2004, EGT has supported NASA's technology tracking and partnership identification activities.

The EGT dataset is a searchable, easy-to-access, and integrated tool that provides concise information on novel technologies and potential partnership opportunities. EGT records include a clear and succinct description 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 enables identification and subsequent connection to technologies, components, techniques, and research personnel. Reports generated from EGT can quickly characterize the types and range of space-relevant research activities within an external government agency, such as DARPA. EGT does not provide a catalog of all government technology development efforts, but it enables a better understanding of trends within national technology development efforts. NASA has often used this capability to help prepare for and provide inputs to partnership exchanges. Table 1 provides examples of technologies currently in the EGT dataset:

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.
Synthetic-bio Robot	An autonomous robot resulting from the fusion of synthetic biology, electronics, and cybernetics.

Technology Horizons and Technology Frontiers

The Tauri Group has worked with NASA to develop a series of reports that increase awareness of future technology trends and identify key organizations and economic sectors contributing to these 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 technology trends, including technology examples and potential partnership opportunities, that could have substantial impacts on future exploration missions.

The *Technology Horizons* report focuses on nearer term technology areas—mature within the next 10-20 years—that have broad participation across the economy and could have a substantial impact on multiple systems for human exploration. Each of the identified "game-changing" technology areas has the potential to enable dramatic performance improvements over projected trends in current space exploration technologies, enabling new capabilities across multiple missions. Many of the potential game-changing technology areas could arise from sectors that are not typically associated with space exploration, enabling new partnership opportunities.

The *Technology Horizons* report was published in 2009 and includes 19 technology areas that group 110 technology concepts. It also includes a watch list of the top technology areas likely to provide unique opportunities for leveraging innovative technologies through partnerships. Example technology areas include:

Technology Area	**Description**
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.
Long Distance Power Transmission	Low/no-loss power transmission to support exploration or transform the national grid.

With similar goals as the *Technology Horizons* report, the *Technology Frontiers* report identifies areas of promising technology advancement, to illuminate new solutions and potential partners. *Technology Frontiers* targeted less mature technology, with a development timeline of up to 40 years. It is more future-thinking in scope and identifies technology areas that could change the paradigm for human space exploration. Technology concepts were captured under broad capabilities that could meet some of the largest challenges to space exploration, referred to as "breakthrough capability" areas. A breakthrough capability describes the technological achievements required to overcome significant challenges facing the future of human space exploration. Each breakthrough capability represents a host of potential technologies and identifies organizations and economic sectors that may enable a key solution to a space exploration challenge. The broad trends for the future proposed in the *Technology Frontiers* report can help space exploration organizations plan for future capabilities and encourage novel partnerships that may lead to innovative technologies.

The *Technology Frontiers* report was published in 2010. It identified 13 breakthrough capabilities, 9 crosscutting capabilities, and nearly a hundred technology concepts that could become future areas for 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.
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.
Everyday Supercomputing – Supercomputing power in everyday handheld devices.	DNA Computing	Parallel processing using millions of DNA 'hardware.'
	Quantum Computing	Using entangled quantum bits to transcend current computing.

Tools like EGT and these reports help identify novel technology areas that meet current and future challenges of human spaceflight and help identify and initiate potential partnerships that may mitigate financial challenges.

NASA's Approach to Technology Partnerships

Because NASA does not have the resources to invest in all the technologies necessary to enable human and robotic space exploration, NASA considers partnership opportunities as an attractive strategy. NASA leverages the expertise of other government organizations, industry, and academia that develop exploration-like technologies in areas that NASA does not. NASA uses partnership tools like those described above to help meet the agency's goal of identifying organizations that are developing revolutionary or game-changing technologies.

NASA's Directorate Integration Office's (DIO) charter includes identifying and initiating partnerships with external organizations that are developing technologies applicable to space exploration. Thus, DIO identified a process to determine what technologies are needed, determine which technologies are not being funded through NASA resources, identify organizations with synergistic technology development, and engage in dialogue with these organizations. In the identification process, DIO develops focused technology white papers that describe technology needs and list external government organizations developing these technologies. The foundation of the white papers is based on years of extensive research on other government agencies' and industries' technology investments. DIO also sponsored the research and development of extensive technology reports, such as *Technology Horizons: Game-Changing Technologies for the Lunar Architecture* and *Technology Frontiers: Breakthrough Capabilities for Space Exploration*, to identify technology needs for space exploration.

In addition to this research, NASA participates in partnering activities to support the agency's goals. NASA participates in various technology-focused conferences to determine what other organizations are doing. NASA also conducts workshops with subject matter experts from various technology development organizations, such as DARPA and DOE, to initiate dialogue with these groups. To assist in the documentation and archiving of this data, DIO sponsored the development of the MATCH database to organize information from external government technology development entities that are developing technologies applicable to space exploration.

As an example of NASA's partnership activities with external organizations, NASA participated in a series of meetings that included NASA's DIO, NASA's Exploration Technology Development Program's (ETDP) Battery Project, DARPA, DOE, and the SION Power Corporation. These participants engaged in dialogue, through technical interchange meetings, to discuss the benefits and disadvantages of using Lithium Sulfur battery technology, current performance parameters, space exploration performance needs and safety concerns with using these batteries in space. Although they did not reach an official partnership or memorandum of agreement, the event was beneficial and a benchmark for NASA's DIO, extending communications with external entities developing critical space-enabling technologies. NASA's practice of open dialogue with external organizations demonstrates the priority of these types of activities and the importance of enabling space exploration through outside technical expertise.

Highlighted Technologies

The EGT dataset, *Technology Horizons* report, and *Technology Frontiers* report each identify novel technologies from economic sectors that are not often related to space exploration but could significantly impact future exploration capabilities. NASA's partnership activities have investigated some of these technologies for potential opportunities, and the agency continues to track others. Several example technologies are highlighted below to demonstrate the range of interesting opportunities NASA has identified and the specific types of information captured in these tools.

EGT Technologies

The following excerpts from the External Technology Dataset include descriptions and applications for four innovative technologies: a transformational approach to manufacturing, novel ground vehicles, nano-structured batteries with significantly increased performance, and a revolutionary bio-bot.

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 a space mission to manufacture unique components or systems in situ. Mission support teams could quickly develop a new component and “ship” it as digital blueprints, reducing the time and cost necessary for shipping replacements. 3-D printing is versatile and can support the manufacturing of products such as fuel tanks or satellite plating.

Currently, 3-D printing applications are increasing in number as capabilities improve and several companies are exploring 3-D printing for various applications. Examples of corporations using 3-D printing for prototype manufacturing include Cisco (wireless routers), Black & Decker (various home tools), and Continental Tire (tire treads).

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 more sophisticated but limited number of larger rovers.

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.

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.

Game-Changing Technologies

The following excerpts from the *Technology Horizons* report provide brief descriptions of four innovative technology areas: life-saving anti-radiation drugs, emerging communication systems, novel collaborative environments, and revolutionary long-distance power transfer techniques.

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

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.

Technology concepts in this area include:

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

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.

Technology concepts in this area include:

- AlloSphere
- Digital Swarming
- Mirror Worlds

Long Distance Power Transmission

Low-power-loss technologies for transmitting electricity over long distances, including wired and wireless solutions, could reduce power requirements for exploration bases and save the national electric grid billions per month. High voltage DC power transmission sends direct current over long distances, only converting to alternating current at required destinations. This minimizes transmission losses and the energy required for AC conversion. A transformative alternative is superconducting power lines, which conduct up to 150 times the amount of energy as copper wires. This results in mass efficiencies and nearly eliminates transmission losses but has potential radiation vulnerabilities. Long-distance power beaming converts electricity to microwaves at the source, then converts back to electricity at the destination. Wireless electricity could offer operational advantages in habitable volumes or enable a number of different transmission concepts in a space outpost scenario.

Technology concepts in this area include:

- High-Voltage Direct Current (DC) Power
- Space Solar Power
- Superconducting Power
- Wireless Power Beaming

Breakthrough Technology Concepts

The following excerpts from the *Technology Frontiers* report highlight three breakthrough capabilities—Seamless Human-Computer Interaction, Super Humans, and Everyday Supercomputing—and provide brief descriptions of six breakthrough technology concepts under these breakthrough capabilities.

Seamless Human-Computer Interaction

Human-computer interfaces enable crew to view data and control machinery in seamless and intuitive ways. Astronauts and mission control personnel 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. 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.

> *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.

Super Humans

Techniques and technologies expand the limits of human capabilities; reducing the need for sleep, increasing alertness, and mitigating stress. Building and maintenance can be accomplished manually, with strength-augmenting exo-skeletons. 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.

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.

Everyday Supercomputing

Advances in supercomputing technologies provide very high processing power and storage for nearly every device and application. Science and vehicle health monitoring capabilities are greatly increased. Huge amounts of data can be processed without having to send it back to Earth. Example technology concepts include:

DNA Computing: An entirely new computing paradigm that involves computing with biologically derived matter. It is a form of molecular computing that uses DNA and enzymes for computation. If successfully built, DNA computers would have an enormous capacity for parallel computing.

Quantum Computing: A new computing platform in which quantum bits (qubits) are used to store information. Researchers estimate that, if successfully built, a quantum computer would take only seconds to solve problems that a silicon computer would take billions of years to solve.

Summary

NASA and other national space organizations are facing significant technical challenges to human space exploration. With diminishing space exploration budgets, these organizations are looking for new tools and techniques to identify externally funded technologies and partnership opportunities to acquire or support technical solutions to exploration challenges. This paper highlighted three such tools—EGT, *Technology Horizons*, and *Technology Frontiers*—that NASA supported to help identify innovative technologies and support current and future partnership activities. These tools are part of a larger, integrated NASA technology partnership approach. Examples of the technologies, technology areas, and breakthrough capabilities showcased in these tools are highlighted in the paper to illustrate the range of external technology opportunities that NASA is tracking. Through successful partnerships, NASA will be able to leverage these technologies and others to provide a cost-effective solution to the challenges of human space exploration.