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Thriving In and From Space for All Humankind

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Abstract

As the National Aeronautics and Space Administration (NASA) continues its quest to extend humankind's knowledge, discovery, and presence deeper into space, there are distinct challenges that must be overcome. Several of the urgent, compelling, and complex human health and sustainability challenges NASA faces in trying to achieve its mission of going forward to the Moon and then onto Mars parallel challenges that currently exist on Earth. These distinct yet overlapping needs coupled with global interest in expanding space exploration provide the perfect incentive for creating a collaborative, multi-sector ecosystem of innovation that addresses human needs in deep space and on Earth.

During the more than 55 years of human spaceflight and the past 20 years of humans continuously living and working in space, many lifesaving and quality of life enhancement technologies have been created, developed, and used on Earth. As our attention shifts to the next phase of space exploration, the U.S. and the international space community are focusing on long duration human exploration of the Moon and beyond. Solutions for advanced and remote healthcare, access to and sustainable management of sufficient food, clean water, and other resources are direly needed both for deep space missions and life on Earth. The disruptive innovation and tremendous growth projected in the space, digital, and sustainability/circular economies have the potential to accelerate transformation globally.

This paper will highlight 1) areas of human life on Earth that have been impacted by innovations and technologies developed to enable and sustain human space exploration, 2) challenges in space and on Earth where multi-sector collaboration could accelerate solutions, and 3) existing and new approaches to create an effective ecosystem of collaboration to speed the development and integration of new technologies into space missions and achieve even greater global societal impact.

Keywords: NASA, spaceflight, human health, sustainability, innovation, partnerships (maximum 6 keywords)

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1. Introduction

Innovations that allowed the successful execution of Apollo 11's 195-hour, 18 minute, and 35 second journey have had impacts beyond the pioneering first visit to the Moon. Flight suits developed to protect astronauts from fire hazards have been adapted for terrestrial breathing apparatuses to reduce inhalation-related injuries; silver-ion technology-based water purifiers are used in spas and pools to kill bacteria and algae; and two-way communications systems developed to send and receive information from satellites have been incorporated into heart pacemakers, allowing reprogramming of implanted devices without additional surgery [1, 2]. Now, with NASA's plans to return humans to the Moon and to pioneer human exploration of Mars, opportunities are ideal—not just for benefiting from the technological and scientific advancements created for spaceflight—but for concurrent development of solutions to benefit missions both in space and on Earth.

The United Nations (UN) Sustainable Development Goals (SDGs) describe challenges faced by humanity, including needs in food security, water quality, health, and access to clean and affordable energy. The urgency and complexity of these global sustainability challenges present a unique opportunity to harness the collective expertise and resources from government, academia, and industry in order to identify and develop solutions across sectoral and topical disciplinary boundaries.

Human spaceflight-related technologies currently in development—for example new environmental and life support systems, and approaches to protect human health, particularly in hostile environments—have been identified as areas where integration with transdisciplinary knowledge and actions can lead to the development of dual-purpose solutions that benefit life on Earth. Instead of conducting scientific research and development in disciplinary silos, and identifying potential applications for Earth independently and after the primary development of technologies for human spaceflight, coordination of efforts in these fields-of-work and collaboration between minds from diverse sectors can greatly enhance time and cost efficiency, as well as amplify the significance of advancements made [3, 4]. In fact, the value in solving complex problems by "integrating knowledge, methods, and expertise across disciplines and forming novel frameworks to catalyze scientific discovery and innovation" has been recognized by the National Science Foundation as one of its "10 Big Ideas" [5]. Recognizing the benefit of coordinated efforts amongst other federal agencies that have similar needs, NASA signed Interagency Agreements with the Department of Health and Human Services, in 2018, and with the United States Department of Agriculture, in 2019, to explore cross-agency areas of mutual interest. These collaborations demonstrate the overlapping human challenges faced on Earth and in space.

Enthusiasm for human spaceflight and commercial flights, together with civic and corporate drives for improving human quality of life can be harnessed for concurrent explorations to tackle human spaceflight and terrestrial challenges. Since its inception, NASA has collaborated with private companies for the advancement of scientific exploration and the benefit of humans in space and on Earth. The agency is building on this legacy today by engaging in partnerships with the commercial sector to advance capabilities in space and to maximize benefits here on Earth [6, 7]. Furthermore, NASA is a leader among U.S. federal agencies in interacting with the private sector through public-private partnerships (PPPs), and through innovative mechanisms, such as open innovation opportunities including prize competitions, to identify and support promising ventures.

Today, NASA is committed to its next mission of taking humans to the Moon and beyond. Commercial enterprises are investing in space and concurrently value sustainability and human advancement on Earth. Together with NASA's rich history of collaboration across organizational boundaries, the stage is set for a new era of addressing ambitious challenges jointly and more effectively. This will not only enable human exploration to the deep corners of our universe, but also bring sustainable and affordable solutions to people on Earth.

2. Human Health Challenges: How Solutions for Spaceflight can Benefit Earth

Human populations around the world today face multiple health challenges, ranging from detrimental effects of air pollution, undetected and untreated mental illnesses, infectious diseases, and lack of basic health care in remote settings. Many human health challenges experienced on Earth are similar, and in some cases accelerated when humans enter space. These formidable challenges test astronauts' capabilities of not merely surviving but performing rigorous scientific exploration missions while in space. Facing changing gravity fields, living in isolation and confined spaces, and being exposed to space radiation requires the crew to have optimal pre-flight health and access to in-flight care. Since its inception, NASA's research has yielded technologies that enhanced medical practices, including new materials, diagnostic tests, sterilizers, and exercise equipment, that have benefited healthcare practitioners and patients across the globe.

Medical care systems for long duration deep space missions to the Moon and Mars will build on and expand the capabilities that exist aboard the International Space Station (ISS) to include ambulatory (outpatient) and dental care, emergency medical and trauma response, and advanced life support. These systems would also provide enhanced Earth-based support, in-space support, medical computer-aided artificial intelligence (AI) systems, and Earth-to-remote locations telemedicine capabilities that use state-of-the-art telecommunication systems for consultation in diagnosis and treatment. Furthermore, as time spent on other planetary surfaces increases, medical care capabilities would also likely expand to providing laboratory analytical capabilities, anesthesia, surgery, and improved pharmaceutical support. For example, research and advanced development to extend shelf-lives of certain pharmaceuticals and blood products and to develop medical countermeasures against the biological effects of radiation and other oxidative stressors (e.g., dust) will be required and are applicable to address related human health challenges on Earth [8].

When envisioning prospects for meeting the complex health and environmental sustainability challenges that are faced in space and on Earth, it is important to consider the profound impact the internet and the digital economy have had on the world since the internet's genesis just 20 years ago. The digital economy—which is valued at $3 trillion—is an essential and crucial enabler and by product of space exploration [9]. Advances made in the digital environment have and will continue to impact every aspect of life in unimaginable ways. The space sector has begun to expand its technological reach and impact the broader economy. In less than five years, quantum computing is estimated to produce one of the most radical shifts in the history of science, likely outpacing any advances experienced to date with prior technological revolutions, such as the advent of semiconductors. Quantum computing will solve problems that would take even the most powerful classical supercomputers millions or even billions of years to solve. This capability will be able to simulate and test intricate processes of the universe in exacting detail, including complex biology, chemical reactions, and the spread of pandemics, in ways that were impossible with classic computers [9].

In its annual Global Innovation Index, released July 24, 2019, the UN's World Intellectual Property Organization identified five trends driving innovation in global healthcare, including 1) Information revolution enabling remote medical treatment and expanding clinical databases for use in research and development of new treatments; 2) Artificial Intelligence to predict and diagnose diseases earlier and with increased accuracy; and 3) Precision medicine enabling the development of personalized, targeted treatments; 4) Consumerism influencing providers and tech companies to offer higher quality, less expensive services; and 5) Evolving business models: In contrast to the siloed structure of the past, healthcare stakeholders are partnering with and investing in one another, making the entire healthcare system more efficient and better aligning incentives across the board [10]. These trends and investments in digital health solutions like electronic health records, digital therapeutics, telehealth, AI wearables, and blockchain for the healthcare industry closely parallel the innovative solutions needed to keep astronauts safe and healthy on long duration space missions. Collaboration between terrestrial healthcare industries and NASA to discover and test new technologies and processes can not only help accelerate the development of new products and services for spaceflight, but also quicken the applications of these new technologies into innovative and creative solutions for Earth [10, 4].

2.1 NASA's Role in Origin of Modern Telemedicine and the Potential for Improved Access to Healthcare in Vulnerable Regions

Recent technological advances including web development and mobile devices that allow social networking, folksonomy, interoperability, and synchronous and asynchronous audio-visual communication have contributed to rapid evolution of telemedical practices [11]. NASA has played a key role in the development and expansion of telemedicine, dating back to the agency's earliest days. As a requisite for spaceflight, telemedicine began with the goals of monitoring astronaut health while allowing predetermined engineering tasks to be accomplished and ensuring astronauts' safe return to Earth [12]. Advancements in near real time communications, have allowed physicians on Earth to provide astronauts continuity of care from before and after their missions [13].

Today, NASA continues to develop solutions to provide astronauts optimal in-flight care, thereby ensuring safe and productive space missions. As astronauts residing on the ISS communicate with ground support for medical care, these and similar practices continue to be explored for providing care in remote, extreme, or other resource-limited settings. For example, ISS technologies and protocols such as data collection via on-board systems and relay to ground-based medical officers have been applied in terrestrial environments [14]. NASA partnered with the Virginia Commonwealth University-based Medical Informatics and Technology Applications Consortium and developed remote anesthesia monitoring for the gall bladder removal procedure of a patient in Sucua, Ecuador. Real-time internet links allowed the detection of a potentially-life threatening anomaly in the patient's heart rhythm, and its subsequent correction by the surgical team [15]. Similarly, the experienced physicians can apply NASA telemedicine technologies to offer remote guidance for medical procedures in locations where imaging technology and internet connectivity is present, but local expertise is lacking.

Advancements in telemedicine that allow crew medical officers and other crew members to use remote guidance to provide routine medical care, as well as care in the case of illness or injury, can help overcome geographic and socioeconomic barriers and expand access to high-quality medical care on Earth. Capabilities that allow physicians with specialized expertise to assess and treat patients in space, can be applied to the care of terrestrial patients over distances. While specialists concentrate in larger cities, telemedicine technology infrastructure can be applied to provide care in underserved areas, rural areas, thus improving disparities in healthcare [13]. Similarly, telemedicine capabilities broaden the reach of physicians to patients with limited mobility, including those with disabilities or those in nursing homes. In fact, as the expanding elderly population in the U.S. begins to place healthcare demands that exceed beyond current supply, telemedicine innovations, as well as new capabilities in data analytics are enabling providers to practice more efficiently, without compromising patient outcomes [4]. Finally, telemedicine also has the potential to reduce costs, both for providers and patients. While physicians may have greater efficiency and lowered maintenance costs operating virtually versus in brick-and-mortar offices, patients can benefit from reduced travel expenses, and fewer missed work hours or days [16]. Recognizing these benefits, 60% of health institutions and hospital systems are already using some form of telehealth, and by 2020 all large employers are projected to provide telehealth coverage [17].

Telemedicine capabilities for space and Earth applications are not limited to consultations and doctor-patient communications. In fact, technologies in development include advanced robotic capabilities for conducting medical procedures with long-distance remote guidance, many of which can benefit from NASA's scientific knowledge and operational expertise. Canadarm 2, the second-generation version of robotic tool Canadarm, which was launched in 1981, was crucial in assembling the space station and continues to be used to move supplies, equipment, and astronauts on the ISS. Dextre, a robotic 'handyman', rides at end of Canadarm2, and can perform precise and delicate tasks, all remotely controlled from Earth [18, 19]. Technologies inspired from these space tools have transformed medicine – for example, neuroArm, patented in 1997 can perform image-guided, computer-assisted neurosurgery, allowing integration of MRI data in the OR and eliminating the need for disrupting the rhythm of a surgery to take real-time images [20]. A second technology, the Image-Guided Autonomous Robot (IGAR), is a digital surgical tool that enables surgeons have greater access, precision and dexterity for performing highly accurate, and minimally invasive procedures [21, 22]. Most recently, Modus V, an automated, hands-free, robotically-controlled digital microscope is being developed to provide surgeons better views while treating patients with brain and spine pathologies [23, 22].

Collaboration between telemedicine experts for space and for terrestrial medicine can greatly advance enhancements as both settings can serve as complementary testbeds for new technologies. As NASA plans for new missions beyond the lower Earth orbit, expected challenges of communications delays and the long return time to Earth necessitate a robust and autonomous medical infrastructure to conduct fitness assessment, and monitoring, diagnosis, and treatment of medical conditions, including common complaints of motion sickness, skin irritation, and back pain, all independent of real-time support from Earth. NASA scientists are already developing procedures and medical devices to provide health support and medical interventions during the extended-duration spaceflight to the Moon and Mars. Technologies in development include an on-board software system to serve as a “triage” assistant – the Medical Decision Support System (MDSS) – providing augmented intelligence for planned and emergent clinical care [24].

2.2 Ultrasound Technology for Spaceflight and its Application on Earth

Medical devices developed for spaceflight are optimized in several areas including minimalized volume, consumables, power consumption, and functionality in sub-g and micro-g environments. Existing devices are frequently retrofitted with accessory technologies that result in improved operation, maintainability, as well as automation features and enhancements to human-device interactions making them more comfortable and easier to use [25]. These technological and procedural advances hold tremendous value for applications in areas where resources are limited.

For example, given the lack of medical resonance imaging (MRI) or X-Ray machines on the Space Station, astronauts and crew-health operations teams had relied on imaging from an ultrasound that had been aboard the station since 2002. Ultrasound is radiation-free, cost effective, repeatable, has reliable results, and is less operator-dependent than techniques like MRI [13]. Given the need for diagnostic accuracy to detect and evaluate over 250 pathologies ranging from cardiac, pulmonary, ophthalmologic, to digestive, dental, and skeletal conditions, NASA and researchers made improvements that made data relays to ground control more efficient, found ways to use water in place of ultrasound gel, and modified devices so that they were operable by non-medical professionals [14, 26].

NASA’s Advanced Diagnostic Ultrasound in Microgravity (ADUM) experiment—led by Dr. Scott Dulchavsky of the Henry Ford Hospital in Detroit, Michigan—tested the accuracy of ultrasound in monitoring organ and bone health for clinical conditions expected during spaceflight, and also tested the ability of non-medical crewmembers to operate the ultrasound device with minimal training, and some audio guidance from a certified ground sonographer. The Onboard Proficiency Enhancer (OPE) program—a software e-learning training application—reviewed equipment setup, basic and advanced ultrasound principles, anatomy, exam-specific suggestions, as well as companion cue-cards to share proper ultrasound techniques with learner [26, 27]. Lessons from the ADUM experiment have had significant implications on Earth. Training methodologies developed for non-medical crewmembers, including the OPE, have been incorporated by the American College of Surgeons Committee on Education into a computer-based training for surgeons to provide core training in ultrasound imaging.

Today, the original ultrasound device on board the ISS has been replaced by the Ultrasound-2, a smaller and more capable device that was launched in 2011. The newer Ultrasound-2 is a modified version of the commercially available Vivid q ultrasound, produced by General Electric Healthcare. In order to maximize its increased capabilities, for example, two-dimensional (2D) and Doppler imaging, smart-depth, as well as panoramic scanning, NASA’s Human Research Facility devised step-by-step instructions on the ultrasound’s use and features [28].

Beyond the ISS, ADUM methodologies have also been used by athletic trainers of the Detroit Red Wings hockey and the Detroit Tigers Baseball teams, where a portable ultrasound device in the locker rooms, athlete-specific cue cards, and tele-ultrasound links to the Henry Ford Hospital in Detroit, Michigan, have allowed remote guidance-based evaluation of common sports injuries. The United States Olympic Committee also used ADUM technologies to evaluate and provide care during at the Torino, Beijing, and Vancouver Olympic Games. Furthermore, ADUM’s remote expert guidance paradigm has been adapted for use in remote locations on Earth, including at Mt. Everest, in the High Arctic and Antarctic locations, with promise for applications for rural medicine, and capabilities to triage casualties during a disaster, and guide patient transport for the military [27, 29].

ADUM’s lead scientist, Dr. Dulchavsky, has since focused on further adapting ultrasound technologies and ADUM protocols for use in Earth’s most remote locations. In partnership with the World Interactive Network Focused on Critical Ultrasound (WINFOCUS), he has helped train over 20,000 physicians and other personnel, termed ‘physician extenders’ in 68 countries around the world, including in Brazil in a statewide healthcare project in partnership with the Secretary of Health of the State of Minas Gerais. WINFOCUS has continued to develop and adapt ADUM techniques for large-scale integration around the world through low-cost applications, resulting in empowered local healthcare providers, and more patients receiving timely and quality medical care [30].

Terrestrial medicine can not only benefit from cross-cutting advancements developed for long-duration spaceflight, but also co-develop these advancements. In fact, NASA’s Human Research Program is partnering with the Translational Research Institute for Space Health (TRISH) to identify and apply promising terrestrial technologies towards risk mitigation during human spaceflight [31]. TRISH has identified Level Ex, the creator of medical video games for physicians, to adapt their capabilities in data-driven simulation and rendering of virtual patients and devices to include space conditions, creating a resource to help astronauts reduce reliance on assistance from the Earth, and handle medical emergencies in space. The company's expertise in state-of-the-art medical technology cognitive neuroscience will be applied to development of modules to train and educate astronauts around specific medical scenarios in space, and procedures to address them. In return, Level Ex hopes that "discoveries and advancements [made] will make [their] technology more robust, which will benefit terrestrial medical education" [32].

2.3 Human Health Research and Applications for Preventative Care, Aging Research and Medicine

Astronauts training to return to the Moon and to Mars are preparing mentally and physically to face the multitude of hazards that come with deep space exploration. Space travel and extended stays in various gravitational fields, exposure to radiation, and life in hostile, closed environments can lead to physiological changes that affect organ structures and functioning including the heart, eyes, and blood vessels. NASA's Human Health Countermeasures program, in partnership with the research community and external organizations, is working to understand and develop countermeasures to mitigate these adverse health effects associated with spaceflight [33].

Human spaceflight presents unique challenges of increased risk of infection. Exposure to microgravity, radiation, and stress, microgravity-induced changes in microbial pathogens' virulence, growth kinetics, and biofilm formation weakens the immune system and increases astronauts' risk of infection. Further compounding this risk is long duration stay in a confined space with an abundance of high-touch surfaces and recirculated air and water. Pre-flight and in-flight countermeasures including vaccination protocols, screening and decolonization and/or treatment, specialized infection control education, and regular exercise programs can reduce this risk [34]. Given the significant global burden of infectious diseases, with 26% of all deaths worldwide caused by communicable diseases, lessons learned from infection control measures in space can and should be explored for applications in terrestrial settings [35].

Pre-flight crew health optimization as well as primary prevention and prophylactic measures during the mission will reduce the risk of illness occurring during a mission. Adaptations that build resilience and resistance to the effects of spaceflight environment can have significant terrestrial applications. Preventative care, for example, in regard to appropriate nutrient consumption and specialized exercise regimens can help prevent bone mass loss in astronauts. These practices can also be applied on Earth to prevent osteoporosis, which is common in women over 55, and men over 65. The Japan Aerospace Exploration Agency is currently exploring the use of preventative countermeasures developed for space medicine to fight osteoporosis on the ground [36]. Astronauts on long-duration space missions share common challenges faced by aging populations including osteoporosis-like physical wear and tear, muscle loss, cardiovascular issues including stiffening of arteries, and a weakened immune system. While the progression of pathology is slow in humans on Earth, these processes occur rapidly in astronauts in space. By characterizing the molecular pathways involved in spaceflight related changes, investigators can develop countermeasures and therapies to protect not just astronauts in space, but also patients with age-associated disorders on Earth [37].

The National Center for Advancing Translational Sciences (NCATS)-supported researchers are also investigating aging and spaceflight-related physiological changes through a novel technology—three dimensional (3D) platforms engineered to support living human tissues and cells, called tissue chips or organs-on-chips [38]. These micro-physiological systems are currently aboard ISS and are serving as functional unit proxies to investigate the effects of microgravity on the human body. The tissue chips can serve as models to test the efficacy and toxicity of drugs-in-development both on the ground and in space. The collaboration between the National Institutes of Health (NIH) and the Center for the Advancement of Science in Space (CASIS) has resulted in automation and miniaturization of the tissue chip technology, allowing this tool to be operated in space and transported to other locations on Earth. Automated experiments using the tissue chips will help elucidate pathologies faced by both astronauts and aging humans, as well as help test therapeutics for conditions including cardiovascular disorders, muscle wasting, and gut inflammation. The potential of these tissue chips extends beyond general understanding of biomedical processes. Future space travelers could carry personalized chips that could be used to monitor changes, and to test possible countermeasures and therapies prior to administration [39].

Understanding diseases requires investigating both genetic and environmental factors contributing to the pathological states. While genetic research has been robust and successful through ambitious efforts like the Human Genome Project, understanding the effects of the environment is challenging. Spaceflight can transform environmental research as it provides exposure to extreme conditions of microgravity and intense radiation, and results in rapid physiological changes, many of which seem to reverse upon return to Earth [40]. Ongoing and future studies in space hold great promise in advancing our understanding of aging and disease, and in the development of novel preventative and therapeutic interventions for challenges in space and on Earth.

Researchers from the international community, Fortune 500 companies and small companies, research institutions, government agencies, and others partner with NASA to leverage the ISS National Laboratory's unique microgravity research platform where every variable, including gravity, can be manipulated to lead to new discoveries to address complex health problems on Earth. A program through the National Cancer Institute's Chemical Biology Consortium will conduct multiple protein crystallization experiments that could result in the accelerated discovery of new therapies for a number of different cancers. The Mayo Clinic is undertaking research aboard the ISS to better understand the resistance of cancer to chemotherapy, which could set the stage for developing new and improved therapies. Working with the National Institutes of Health, numerous protein crystallization studies are taking their ground-based efforts to the ISS, seeking larger and more uniform crystals to better visualize new drugs to control cancer growth and improve both drug discovery and delivery methods. Protein crystallization experiments on the ISS have aided in unique vaccine research, which has provided insight that may benefit vaccine research for diseases caused by pathogens such as Salmonella and HIV. A project from the pharmaceutical company Merck & Co. utilized the ISS National Lab to grow millions of highly ordered, uniform crystalline particles of the therapeutic monoclonal antibody Keytruda® with the potential to improve drug delivery for patients [41, 42].

3. Environmental and Sustainability Challenges and the Opportunity to Develop Dual-Purpose Solutions

NASA has been committed to sustainability for the past twenty years. The primary goal of its sustainability policy is *"…to execute NASA's mission without compromising our planet's resources so that future generations can meet their needs. Sustainability involves taking action now to enable a future where the environment and living conditions are protected and enhanced…NASA has been on the path to achieve long-term sustainability goals for many years through numerous efforts in energy conservation, recycling, water management, pollution prevention, design and construction, maintenance and operations, master planning, and electronic stewardship.* [43]*"*

Faced with mounting challenges and pressure from governments, nongovernmental organizations (NGOs), investors, employees, and customers to be more aware of the environmental and social impacts of business activities, companies are beginning to prioritize sustainability efforts, while also seeking opportunities for growth. As stated in the September 2009 issue of Harvard Business Review, "Indeed, the quest for sustainability is already starting to transform the competitive landscape, which will force companies to change the way they think about products, technologies, processes, and business models [44]." Industry leaders are increasing connecting long-term corporate success to protecting their communities and supporting a healthy environment. With the release of Business Roundtable's most recent Statement on the Purpose of a Corporation, 181 CEO's, including those from companies including JPMorgan Chase & Co., Johnson & Johnson, Proctor & Gamble, Boeing, Lockheed Martin, IBM, Google, and Merck, have publicly committed to supporting the communities in which they operate and have vowed to protect the environment by embracing and implementing sustainable practices [45]. As an additional indication of corporate commitment to sustainability, there are more than 9,500 companies and 3,000 non-business signatories to the UN Global Compact (to work toward achieving the SDGs) from over 160 countries. The evolution of consciousness toward commitment to action has taken time and is building momentum. The opportunity has never been greater to achieve transformative solutions to complex sustainability challenges to support life on Earth and in space [41, 42].

3.1 NASA Technology Improves Water Quality Around the World

The challenges of understanding the basic dynamics of how fluids behave in space and the ability to process liquids and produce clean water in confined quarters using reliable systems in a microgravity environment has yielded surprising benefits for astronauts in space as well as for people on Earth. The current methods used to test and process water on the ISS have not only translated into advancements in water monitoring and purification on Earth, but have also led to advances in medical diagnostic devices [46].

Access to clean water is a critical need essential for all living organisms in space and on Earth. Supplying this very basic necessity has proven to be a tremendous challenge throughout the universe from low Earth orbit and deep space environments to every corner on Earth. Furthermore, from the most technological advanced and economically robust nations to the smallest and most remote locations in developing nations, producing clean drinking water for the masses is an ongoing struggle and nearly one billion people worldwide lack access to safe drinking water [46, 47].

In September 2015, the European Space Agency (ESA) conducted a technology experiment that tested the efficiency of a forward osmosis biomimetic membrane technology that filtered certain semi-volatile substances from condensate aboard ISS. The experiment confirmed that forward osmosis process exceeded the filtration performance of the current ISS water recovery systems that rely on reverse osmosis. Forward osmosis technologies offer a far more resource-efficient means of filtration compared to the more common reverse osmosis techniques. The success of this membrane and filtration method provides a more efficient way to filter and reclaim water in any environment. This helps reduce upload mass of expendable media currently used in water processing on the ISS and is more apropos for future exploration missions where resupply of expendable media is not a viable option. The membrane can potentially achieve a water permeability two orders of magnitude higher than existing reverse osmosis membranes on Earth, highlighting the opportunity for applicability on Earth to expand the fresh water supply through desalination of salt and brackish water [46].

3.1.1 Advanced NASA Technology Supports Water Purification Efforts Worldwide

The ability to efficiently recycle wastewater onboard the ISS reduces the need for costly resupply efforts. Without this capability, the space station's current logistics resupply capacity would not be able to support the standard six-crew-member population. For long duration space travel, resupplying water is not even an option. Today, even the most at-risk areas on Earth (areas without access to clean drinking water) are able to gain access to advanced water filtration and purification systems through technology that was developed for the space station, thereby making a lifesaving difference in these communities. The first of many ground-based water filtration systems using NASA technology was installed in northern Iraq in 2006. The system was developed, licensed and adapted for use in Earth-based water treatment systems by the Water Security Corporation (WSC). Since that initial effort, the commercialization of this technology has provided aid and disaster relief for communities worldwide [46].

An integral component of the purification and filtration process is the Microbial Check Valve (MCV), an iodinated resin that controls microbial growth in water without using any power. The valve performs an important secondary nutritional function for the populace by dispensing iodine into the water. Iodine enhances brain function and helps maintain the hormone levels associated with regulating cell development and growth. Children born in iodine-deficient areas are at risk of neurological disorders and mental retardation [46].

3.1.2 Space Station-Inspired mWater App Identifies Healthy Water Sources

It is now possible to determine the cleanliness of your water using a phone app. The mWater App—which is based largely on ISS technology—is a global resource that is a free, downloadable web app and can be used via the web browsers available on most smartphones. The app was developed as a result of the 2011 NASA-sponsored Water Hackathons, the collaborative efforts of physicians, engineers, technologists and software designers to create new tools to solve the clean water crisis [47]. The app helps simplify the processes of recording water quality results, mapping water sources, and identifying safe water sources near the user's current location. The app can also test for and detect E. coli in 100-milliliter (3.38-ounce) water samples. mWater is a non-profit venture that provides low-cost test kits and monitoring software in support of the global Water and Sanitation for Health (WASH) initiative, was founded by researchers who developed NASA's Microbial Water Analysis Kit—which is a part of the space station's environmental control systems. The kit is a suite of hardware that monitors microbes, silica and organic material in the water supply on ISS and is the basis for the mWater app [48]. During the first year of the beta release testing, more than 1,000 users downloaded mWater and mapped several thousand water sources. Currently, mWater is used by more than 25,000 government, non-profit and academic institutions in 147 countries. Based on space station technology, the mWater testing kit costs $10 uses efficient, mobile techniques to test for contamination in drinking water sources, and produces the largest WASH access database on the planet [46]. Users can map and monitor water points and other critical infrastructure using the free mobile app and data portal.

A key mWater capability was derived from NASA's innovation – the ability to perform accurate testing at near-ambient temperatures. Traditional laboratory water quality tests require an incubation temperature of 37°C (98.6°F). However various studies have shown that any temperature around 25°C (77°F) will produce an accurate result. This is vital for developing countries as incubators are expensive, break down easily, and require reliable electrical power. Tropical nations that suffer from poor access to safe water are now able to test water quality at room temperature, at any time of the year [46]. In fact, what began as a simple app for monitoring water quality data has now grown into a full-featured mobile information-collection and visualization platform for almost any kind of data. The app simplifies the process of recording water quality results, the mapping of water sources, and the identification of safe water nearby. Test results are automatically uploaded to the cloud-based global water database using a phone's Global Positioning System and can identify the precise location of the water source [46].

3.1.3 Addressing Water Contamination

NASA researchers have also designed solutions to restore environmentally contaminated sites. An adverse consequence of rocket maintenance at Kennedy Spaceflight Center (KSC) in Merritt Island Florida—which has been a launch site since the early Apollo missions—is the contamination of surrounding grounds with solvents from the cleaning of rocket engine components. These solvents, classified as Dense Nonaqueous Phase Liquids (DNAPLs), can migrate and contaminate freshwater sources, including ground and surface waters, and remain in the environment long after their release. Addressing this contamination was critical to ensure the preservation of more than 1,500 plant and animal species that inhabit Merritt Island Wildlife Refuge, which is adjacent to KSC. NASA scientists at KSC partnered with researchers at the University of Central Florida and developed an innovative technology to address DNAPL contamination—the Emulsified Zero-Valent Iron (EZVI). EZVI employs nanoscale zero valent iron particles placed in a surfactant-stabilized, biodegradable water-in-oil emulsion. When injected in the soil of contaminated zones, DNAPLs diffuse through the oil emulsion and are de-halogenated by the zero-valent iron, producing ethane and other non-toxic biohydrocarbons [49, 50]. NASA's EZVI technology overcame the challenges of several DNAPL-treating predecessors. Compared to traditional pump-and treat methods, which can require decades of treatment time, steam injection, and radio-frequency methods, which can result in contaminant mobilization, EZVI is quick, effective, cost-competitive, and functions without further damage to the environment.

Following successful lab tests, EZVI contracted with GeoSyntec Inc. through NASA's Small Business Technology Transfer (STTR) program, and through groundwater testing at KSC, demonstrated real-world effectiveness of this technology in successfully removing DNAPLs. The demonstrated and potential value of the EZVI technology has been recognized though several awards, including NASA's Government Invention of the Year in 2005, NASA's

Commercial Invention of the Year in 2005, and the technology's induction into the Space Foundation's Space Technology Hall of Fame during the 23rd National Space Symposium in 2007. Additionally, EZVI has resulted in two U.S. patents, and been licensed by nine companies, making it one of NASA's most licensed technologies [50, 51].

Challenges with DNAPLs contamination exist well beyond the confines of KSC; in fact, DNAPLs are common environmental pollutants, found at thousands of sites across the United States. The technology developed to address contamination resulting from the cleaning of rocket engine parts is now taking on pollutants at dye, chemical, pharmaceutical, adhesive, aerosol, and paint manufacturing sites and dry cleaning, leather tanning, metal cleaning, and degreasing facilities in the U.S., France, and Japan. The ongoing development of EZVI's use in environmental clean-up is another example of how NASA technology is improving life on Earth [50, 51, 52].

3.2 Closed Loop Environmental Support Systems for Space and Applications on Earth

The linear approach — "take, make and waste" — incorporated into most traditional business models has put a chokehold on economic growth through escalating and increasingly unpredictable raw material prices and the expense of depending on less stable supplies of constrained resources. A circular economy is being increasingly adapted by businesses, with a focus on eliminating and redefining the traditional concept of "waste" and recognizing everything has a value. Together, the circular and digital economies present a promising opportunity to create a new "circular advantage" The Business & Sustainable Development Commission predicts that by 2030, at least $12 trillion of market opportunities annually will be linked to the implementation of the UN's Sustainable Development Goals [53, 54]. Incidentally, for the past 20 years, space agencies have focused on developing and improving their closed loop environmental and life support systems (ECLSS) to sustain crew aboard the International Space Station to minimize the quantity of supplies needed from Earth. Preparing for human missions to Mars will require attaining nearly 100% self-sustaining, regenerative ECLSS, as access to resupply during missions will be unavailable for at least 8 months [8]. Adaptation of technologies developed for space to creatively and effectively re-use, recycle, and repurpose available resources can improve management of our scare resources on Earth. Working together through PPPs to solve these space and Earth challenges could accelerate the development and implementation of innovative solutions.

3.2.1 Energy Conservation, Clean Energy and Alternative Fuels

NASA implements processes that are intentional and targeted to ensure energy efficiency in all areas of human space flight and that consciously consider the impacts on natural resources and human life on Earth. NASA's goal is not only to conserve energy but also to conserve and protect natural resources, the environment and conduct human spaceflight missions that are efficient and sustainable [55].

Researchers at NASA are conducting cutting-edge research in the development of clean energy technologies for all of NASA's mission needs, such as biofuels, solar, and wind technologies. NASA researchers and industry partners are continuously creating, developing and testing alternative fuels—including biofuels—for aircraft [56]. The use of alternative fuels, especially in spaceflight, is critical to building a robust human and deep space exploration program that is sustainable. Advancing alternative fuel and other clean energy technologies has several long-term advantages that will impact the environment globally, including: substantially reducing the impact aviation has on Earth's environment, reducing the US's dependency on foreign petroleum, reduction in the generation of greenhouse gases and creating and advancing technologies that promote a sustainable future on Earth [56].

3.2.2 3D Printing

Astronauts aboard the ISS rely on cargo resupply missions to ferry parts, tools, and other supplies from Earth. This process can be lengthy and inefficient leaving the crew waiting weeks or even months for critical maintenance supplies. As human exploration ventures farther into deep space, these cargo resupply missions will become more costly and complex, which has compelled NASA to consider alternate options for providing and replenishing spacecraft supplies.

Three-dimensional (3D) printing provides additive manufacturing technology aboard the ISS. Additive manufacturing is a way of printing 3D components from a digital model. With 3D printing, parts can be built within minutes to hours [57]. The ability to 3D print parts and tools on demand will dramatically reduce the time it takes to get parts to the crew and increase the reliability and safety of space missions, while reducing costs. Creation of a microgravity 3D print-on-demand "machine shop" for long-duration space missions is a vital component for sustainable, deep-space human exploration (such as crewed missions to Mars), where there is availability of Earth-based logistics support is limited. The potential for autonomously printing and assembling structural beams and other large spacecraft components in space is also a potential game-changer by eliminating risky spacewalks by crew and other logistical constraints [57]. In 2022, through a private-public partnership with NASA, Made In Space, Inc. will demonstrate the ability of a small spacecraft, called Archinaut One, to manufacture and assemble spacecraft components in low-Earth orbit [58].

3.2.3 Logistics Reduction and Repurposing (LRR)

All human space missions, regardless of destination, require significant logistical mass and volume that are proportional to mission duration and purpose. As exploration missions increase in distance, duration, and scope, reducing logistics requirements is critical given that the goal is to transport the entire payload on a single launch vehicle. The primary focus of this project is to reduce the initial mass and volume of supplies and reuse items that are launched [59]. The goals of LRR are to engineer common crew consumables, container configurations, and waste management to accomplish several overarching goals: overall reduction of logistical mass, reuse and repurpose logistical items to meet dual functions. Reprocess logistical items to provide a secondary function, increase habitable volume, enhance life support closure, deconstruct logistical materials, and reconstruct them into primary gases as a means of reducing waste volume through venting. A few of the projects are:

Advanced Clothing Systems: The Advanced Clothing System project reduces the mass and volume of clothing by using advanced commercial off-the-shelf fibers and antimicrobial treatments. Longer wear clothing will change the break-even point for laundering (vs. clothing disposal) These new fabrics also improve heat transfer and sweat management during exercise inspiring innovative textiles for the gym and for those working in extreme conditions on Earth [60, 61].

Multipurpose Cargo Transfer Bag (MCTB): MCTB is a project that repurposes logistics-to-living multipurpose cargo transfer bags for on-orbit outfitting. On Earth, the logistics of living create significant trash and have created both resource sustainability and waste disposal challenges. The multiple reuse and repurpose approaches employed by this project to address logistics challenges within the habitable volume of a spacecraft, demonstrate the tremendous potential for such ingenuity to solve similar challenges on Earth. MCTBs can be repurposed in multiple ways including constructing crew quarters, creating privacy and noise reduction partitions, contingency water storage or wastewater processing units, and dense-area project radio-frequency identification (RFID) enclosures for autonomous logistics management. The ability to reuse MCTBs logistics carriers eliminates the need to fly multiple items. For missions beyond low Earth orbit, the vehicle interior habitat volume is relatively fixed and MCTBs enable the more efficient and effective use of this volume. MCTBs also reduce habitation trash generation rates and reusing cargo bags improves acoustics and habitation functionality [62].

*Heat Melt Compactor (HMC)***:** The HMC is a device that compacts and heats trash and converts the waste and used logistical items into useable products. The primary purpose of the HMC is to reduce the volume and microbiologically stabilize the waste. Trash is heated to the point where some of the plastic softens and fills the interstitial voids between non-melted trash. The compacted trash is then cooled, resulting in a dry, relatively solid tile that does not exhibit the spring back of traditional compactors. The predictability of the shape of the tile allows the storage volume to be maximized and used more the efficiently. When the trash is heated, it results in a microbiologically safe tile that can be safely handled by the crew.

The HMC can process both wet and dry trash. The tiles have ~10% hydrogen by mass from the plastics, wipes, and residual food and can be used to provide additional radiation shielding in the spacecraft. Waste items are heated and mechanically compacted into stable tiles that can be used for radiation shielding. Additionally, water is recovered for life support processing. For a one-year mission, it is estimated that HMC could recover ~10 cubic meters of habitable volume, produce over 800 kg of radiation shielding tiles, and recover 230-720 kg of water [63]. This technology is being developed for space, yet the ability of producing a more circular system of inputs and outputs to reduce trash and preserve resources can also be modified and applied to address this need on Earth.

3.3 NASA's Answer to Food Security Challenges

Proper nutrition is critical for astronauts on the long-distance voyages. Nutrition in space is important as it impacts and influences key physiological functions including maintenance and proper function of endocrine, immune, digestive and musculoskeletal systems. Long-duration space missions require quantitation of nutrient requirements for maintenance of health and as a defense against the effects of microgravity. Space nutrition research is critical to advancing the humans space flight program and may also help in understanding the problems of deterioration of people restricted to hospitals and nursing homes. The weightless condition of Earth orbit effects the body in much the same way as extended bed rest [64].

Key areas of space-related nutritional concerns- and nutrient-related challenges, include loss of body mass and depletion of nutrient stores due to inadequate food intake, increased metabolism, and irreversible loss or degradation of nutrients. Health issues directly related to nutrition include bone and muscle loss, cardiovascular degradation, impairment of immune function, and neurovestibular changes. ISS crewmembers are increasingly experiencing vision changes, which has become one of the major concerns associated with long-term space missions [65]. Environmental issues, including radiation exposure and cabin environment (oxygen and carbon dioxide levels, temperature, and humidity) can also have profound effects on nutrients, and may provide areas where nutrition can counteract and mitigate some issues and serve as a countermeasure [66]. When crewmembers perform extravehicular tasks, the spacesuit serves as their spacecraft and associated nutrition risks—high oxygen exposure, limited access to water, inability to eat for up to 8 to 10 hours—rise exponentially [65]. Other challenges associated with long duration space missions revolve around the weight and volume of the food, its packaging and the quantity of water needed for rehydration. Space mission foods are prepared and tested for taste, nutritional value, convenience in preparation, storage life, and microbiological safety [65].

One of the biggest constraints that scientists have to contend with is the lack of refrigeration, which means everything has to be shelf-stable for long durations of time and astronauts' diets are entirely comprised of processed food during a space mission. This not only has drastic physiological implications, but it also has deep psychological impacts. Providing food that is nutrient dense, appetizing and sensory is critical to the overall crew health—mental and physical—while they are on mission. Research also indicates that copious amounts sodium contributes to bone and strength loss in space, and the NASA medical community has found ways to reduce the sodium content in space food while preserving its quality, flavor, and nutritional value [67]. One food popular with astronauts that works well on long duration deep space missions are tortillas. Tortillas are nutritious, have minimal packaging, are easy to store and do not produce crumbs. Unlike tortillas found in restaurants, NASA's are made with less water and specially formulated to be mold resistant, are packaged in nitrogen filled plastic bags, and have a shelf life of approximately 18 months [65].

NASA is working to find improved formulations, better packaging processes and technologies—including cold storage—to help mitigate diet and nutrition related issues. Leveraging both biology and engineering, synthetic biology offers tremendous potential for providing solutions for long duration human space exploration. Two of the potential applications of synthetic biology that NASA is investigating are—one to advance nutrition and one to increase in-space manufacturing capabilities. A system using these capabilities would store nutrients in more stable, dried forms, which a computer can use to print food individualized for each astronaut's specific nutrient needs [66].

3.3.1 Growing Fresh Food in Space

NASA has partnered with the United States Department of Agriculture (USDA) to improve crop performance in controlled environment agriculture systems for ground-based applications as well as in space. This is an important area of research for the US since agricultural crops are significantly impacted by climate change and irregular weather patterns, and application of controlled environments allows farmers to monitor yield and increase efficiency. Many of the technologies developed for space, such as using light emitting diodes (LEDs) to grow plants and applying hydroponic techniques to grow root zone crops like potato and sweet potato, have spun off into multiple terrestrial CEA applications. Likewise, NASA has benefitted from the developments from USDA. Space exploration will be complex and challenging, but by drawing on the talents of the USDA, universities, and companies involved with the expanding CEA industry, humans will one day be farming in controlled environments on the Moon and Mars.

3.3.2 Creating Food from Carbon Dioxide Could Feed Billions

In recent years, science has uncovered the significant impact that the beef — and poultry, pork, and fish — processing industries have on Earth's ecosystems. The meat industry is one of the main drivers of climate change, pollution, habitat loss, and antibiotic-resistant illness. Based on a concept developed by NASA, a new carbon-neutral source of protein may help address this challenge. The advent of a promising source of protein derived from two of the most renewable natural resources—carbon dioxide (CO2) and sunlight—reduces the destruction done to Earth and simultaneously offers the promise of a stable, long-term solution to one of the world's most fundamental nutritional needs [68].

Solar Foods is a Finland based company that makes "Solein" — a proprietary high-protein ingredient — by extracting CO_2 from air using carbon-capture technology, and then combines it with water, nutrients and vitamins, using renewable electricity (solar energy) [68]. The production process for Solein, which began at NASA, allows a natural fermentation process to occur and is free from agricultural limitations, as it is produced indoors and does not rely on arable land, water (i.e., rain), or favorable weather. The company is working with the European Space Agency to develop foods for off-planet production and consumption and are working to bring their method of clean protein production to areas whose climate or ground conditions make conventional agriculture impossible.

3.3.3 Global Food Security

NASA recognizes that global food security and resilience represents a major societal challenge for the coming decades and has established an agency-wide Food Security Office to partner with Harvest [69]. Harvest is multidisciplinary NASA-funded program led by the University of Maryland to enhance the use of satellite data in decision making related to food security and agriculture. One of the main objectives of the program is assisting with inter-agency coordination to advance state-of-the-art technology to public and private agencies focused on global food security challenges and to ensure that food security science and applications are incorporated into new satellite missions [70].

4. The Strength of Collaborative Innovation Present and Future

The challenge of human space exploration drives a continuing effort to design more capable, safe, reliable, and efficient systems with utmost ingenuity, making space a hotbed for disruptive technologies. Partnerships and capabilities developed through human space exploration have resulted in solutions to challenges on Earth and continue to create new opportunities for addressing global challenges. In fact, with the pace of growth and innovation in the space, health, and digital sectors, as well as the improving regulatory environment and increasing reliance on PPPs, there are opportunities to expand the ecosystem for greater collaboration and global, societal benefits.

Through a myriad of initiatives over the past decade, the U.S. Government has prioritized its efforts to ensure government data is more accessible to the public, innovation is encouraged, regulatory burdens to industry are reduced, and partnerships with the private sector are encouraged. NASA has been shifting its approach for developing the capabilities it needs for its missions from seeing space as a niche quest to seeking to find and leverage commonalities and innovation from other industry sectors. An important part of NASA's strategy is to encourage and motivate the commercial space industry to partner with the agency as it works to achieve its strategic goals and objectives for expanding the frontiers of knowledge, capability, and opportunities in space.

A revolution in how space missions are funded, and commercialization is underway. Three overarching thrusts are driving innovation in the space sector: 1) the persistence of national security and science objectives (as more countries are investing in space programs); 2) the expansion of downstream space applications (user requirements); and 3) the pursuit of further human space exploration [71]. Improvements in managerial practices and miniaturization of technology have reduced launch and payload costs, dramatically reduced barriers to entry, and encouraged competition—resulting in more private investments in space, greater innovation and cost reductions. From 2012 to 2017, investments in space start-ups alone was nearly three times greater than the total investment from 2000-2012 (Bryce Space and Technology, 2018). Spurred by major technological advances and the promise of triggering even greater breakthroughs in innovation, new players, including developing countries, private firms and even individuals are now participating in an industry once dominated almost exclusively by powerful countries. Multiple Wall Street investment banks have valued the current space market at ~$350 billion and forecast the market growth will exceed $1 trillion by 2040 [72]. The increased access to space opens up new markets for terrestrial application.

4.1 Public-Private Partnerships: Building Capabilities for Human Exploration of the Moon and Mars

Since its inception, NASA has collaborated with industry, academia, other Federal agencies, and international space agencies for the advancement of scientific exploration and the benefit of humans in space and on Earth. Over the past decade, however, NASA has been shifting its approach to identifying ways to utilize capabilities and innovation available from other industry sectors. The agency collaborates with businesses to develop technologies and innovations that align both with the businesses' corporate plans and NASA's strategic goals. These U.S. companies contribute their own funds and resources to projects and thereby become co-investors in enabling NASA's next generation of science and human exploration missions. NASA interacts with the private sector through PPPs, and through innovative mechanisms, such as open innovation opportunities to identify and support promising ventures. While NASA's goal for its partnerships is to spark new ideas, reduce research and development costs for both itself and its partners, and create capabilities and technologies to support a commercial market, the agency's ultimate goal is to speed the integration of new technologies into space missions [73].

NASA uses multiple mechanisms to advance technologies and capabilities needed for its missions. The Human Exploration and Operations Mission Directorate is using a PPP model for its Next Space Technologies for Exploration Partnerships (NextSTEP). NextSTEP is open to all categories of U.S. and non-U.S. institutions—including NASA Centers and other Federally funded research and development centers, government agencies, companies, universities and nonprofit organizations [74]. NASA's Space Technology Mission Directorate (STMD) solicits, builds, and seeks partnerships with businesses of all size to accelerate the development of technologies that have promise, may serve to meet a future NASA space exploration need, and will advance the U.S. space sector as a whole [75]. One of the assets that STMD employs to achieve these objectives is NASA's Center of Excellence for Collaborative Innovation (CoECI). CoECI was established in 2011 at the request of the White House Office of Science and Technology Policy, following a highly successful pilot initiative to test the potential for crowdsourcing to accelerate and augment research and development efforts at NASA.

Today, within CoECI, under the umbrella of the NASA Tournament Lab, NASA also assists other federal agencies with all aspects of challenge design and implementation, including problem definition, determination of incentives, and submissions evaluation. The NASA Tournament Lab allows engagement of private open innovation platforms for challenge execution [76]. An exciting way for NASA and the private sector to jointly address challenges in space and on Earth is through these open innovation mechanisms including prize competitions. Challenge competitions open the solution space beyond NASA's traditional boundaries, enable sponsorship funding by multiple parties, and promote private sector development by often allowing the entity that created the solution to retain intellectual property rights to their products and services. By hosting challenge competitions, NASA can more effectively reach beyond the space sector to other business sectors to create novel opportunities for innovation, collaboration, and creative problem-solving. The 3D Habitat Challenge and the Earth and Space Air Prize are two examples that demonstrate how NASA has used open innovation to address complex challenges that have applicability on Earth and in space.

With a total prize purse of $3.15M, NASA recently completed a very engaging multi-phase 3D Printed Habitat Challenge for a Mars mission. The competition has already resulted in tremendous new innovations for terrestrial applications, including an eco-friendly habitat using biodegradable building material grown from crops [77, 78]. Additional challenges are in development to address energy and nutrition on extended lunar missions. There's a growing opportunity to leverage corporate, philanthropic, and government interests in finding solutions to complex challenges that have significant societal impacts.

NASA has also partnered with the Robert Wood Johnson Foundation, nation's largest public health philanthropy, to sponsor the Earth and Space Air Prize, a competition to identify a solution that improves air quality and health in space and on Earth. This technology innovation challenge recently awarded the winner $100,000, for robust aerosol sensors to monitor air quality, and prompt actions through alerts when needed. This partnership project successfully demonstrated the potential of public-private join ventures to help address ambitious challenges, such as explore new technologies for a fundamental determinant of human health – the air we breathe [79, 80].

4.2 Potential to Grow the Earth-Space Ecosystem of Innovators, Collaborators and Implementers

As NASA continues to build on its legacy and advances towards sending astronauts on deeper and longer space exploration missions, technologies developed to keep these pioneers safe will undoubtedly hold serendipitous promise as solutions on Earth. PPPs between space agencies and industry, philanthropic organizations, and non-government organizations will not only help accelerate the development of new products and services for spaceflight, but also quicken the applications of these new technologies into innovative solutions for Earth. The US government has made investing in, facilitating, and strengthening multisector partnerships a priority [81]. The potential impact of expanding the Earth-space ecosystem to advance innovation and address societal challenges was also discussed at the United Nation's International Space Exploration Forum in Tokyo in March 2018 [82]. Among the recommendations that resulted from the forum was that "*The Committee on the Peaceful Uses of Outer Space should consider including on its agenda an item entitled "Space exploration and innovation."* Strengthening global partnerships between Governments, the private sector and civil society as a means for implementing and revitalizing sustainable development is also identified in UN SDG 17 [83].

4.2.1 Leverage Existing Networks

There are a growing number of international forums, NGOs networks, industry consortia, and corporations that are focusing on innovating and implementing measures to achieve greater environmental sustainability. There is also a well-established and growing sector focusing on applying Earth observation data to address societal health, food, water, and disaster protection and recovery needs. In addition to the work of NASA's Earth Science Applications Program, human spaceflight program's CubeSat launch initiative contributes to achieving greater societal benefits by offering innovative technology partnerships that allow small satellite payloads built by universities, high schools, and non-profit organizations to be launched into space [84]. In fact, the ISS served as a technology development testbed for Planet Labs, a commercial provider of Earth observation photography from low-Earth orbit by using hundreds of small, relatively inexpensive satellites. The ecosystem that has been established to take advantage of Earth observation data to solve challenges on Earth may benefit from applying human spaceflight technologies, as well. Exploration and discovery of our solar system is a collaborative international endeavor, as demonstrated by the International Space Station. All countries are interested in advancing technologies of their countries and demonstrating the benefits of space to its citizens. NASA engineers, scientists, and program managers have been working in partnership with other nations for decades and will continue to be essential to our science and human exploration plans for decades to come. Since 2007, NASA has been coordinating the US human exploration priorities and plans with 14 space agencies around the globe through the International Space Exploration Coordination Group [85].

NASA will increasingly rely on partnerships with industry and the international community to achieve its ambitious missions to send humans to explore the Moon and Mars. The urgency, magnitude of opportunities, and incentives to develop innovative solutions for human spaceflight apply to and overlap with those on Earth. While there are other government and international organizations focusing on meeting complex challenges to achieve global societal benefits, increased connections among them and with the robust, growing and innovative industry sectors will surely pay dividends. Any new or existing organization can initiate efforts to expand this Earth-space ecosystem for societal benefit. There are tremendous healthcare needs facing the US and facing humans for long duration deep space exploration, as well as environmental sustainability needs. The urgency and magnitude of these needs creates financial and societal incentives that will drive innovative solutions and greater collaboration has the potential to accelerate solutions and implementation for space and on Earth [86].

4.2.2 Sponsored Challenges

In collaboration with and sponsorship by corporations, philanthropic organizations, and/or consortia, NASA could assist in conducting challenges to address complex challenges in space and on Earth. One example would be to establish analogs on Earth to develop and test sustainable, circular capabilities needed for deep space human exploration. The analogs could be the basis of "Habitat Technologies for Humanity" and might begin with the shelter being the next generation of 3D printed habitats. Within the shelter, closed loop technologies would be demonstrated for remote human health, food, water, nutrition, power, communications, etc. Low cost innovations could be delivered to communities facing what might be considered "outpost-like conditions [8]." There could be challenges for each of these areas with sponsorship by corporations and philanthropic organizations with a commitment to addressing these challenges on Earth as well as who support human exploration of the Moon and Mars. As capabilities increase, through several challenge phases, the winning team(s) could be considered for testing in space. Through these relationships and presence of these analogs in communities around the US, and perhaps the world, more citizens would be engaged in experiencing the challenges and fragility of human space exploration, as well as more engaged in solving global societal challenges. When the first woman and next man walks on the moon, many more people will have participated in making that possible and will have benefited throughout the journey.

5. Conclusion

Development of dual-purpose solutions to address challenges in space and on Earth is an ambitious task that requires determination, enduring commitment, ingenuity, and widespread participation. Human space exploration has the ability to catalyze the attention and inspire people across the globe, as was most recognized when Neil Armstrong first stepped on the surface of the Moon 50 years ago. The technologies that were developed to achieve those Apollo missions and that have enabled continuous human presence in space since 2000 aboard the ISS, have had profound impacts on our lives on Earth. Space was viewed as its unique and the best and brightest worked together at NASA and its contractors to develop solutions. Most of the space technologies were ingeniously identified as applicable to addressing needs on Earth after being developed to meet space needs.

A shift has been taking place over the past decade. Today, PPPs and new mechanisms such as open innovation, offer the opportunity to engage more fully to develop innovative solutions that can more concurrently transform our lives and the environment. Business sectors continue to cross boundaries of definition as technologies and the digital economy enables new possibilities for transforming what we know and how we conduct the transactions of our lives. The space economy is growing and creating new opportunities for inclusion around the globe as greater access to technologies such as communication and internet service become available and affordable. Corporations are reaching the tipping point where not taking action to advance sustainability, such as achieving the UN SDGs, will damage their bottom line. Numerous international and domestic new companies, non-profit, philanthropic, and non-government organizations have been created and continue to be created to address the human health and environmental sustainability challenges being faced around the world.

Human exploration of space requires courage, ingenuity, resources, and a commitment by many teams of people to attempt what has not yet been done and most believe is not possible. Our journey to sustainably explore the Moon and Mars can be inspiring and transformative for everyone on Earth as we seek to ensure that humans thrive in and from space.

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