Moonshot R&D MILLENNIA* Program

*Multifaceted investigation challenge for new normal initiatives program

"Connecting every person, Earth, and outer space: a society that coexists with and benefits from space"

Initiative Report

July 2021

Goal review team: "Toward an outer space that all can freely access and use."

Team leader: Takaya Inamori (Associate Professor, Graduate School of Engineering, Nagoya University)

Subleader: Kiyoshi Kinefuchi (Associate Professor, Graduate School of Engineering, Nagoya University)

Team members: Ken Matsuoka (Associate Professor, Graduate School of Engineering, Nagoya University)

Satoshi Ikari (Assistant Professor, School of Engineering, The University of Tokyo)

Kazuhiro Nakazawa (Associate Professor, Graduate School of Science, Nagoya University)

Taro Matsuo (Associate Professor, Graduate School of Science, Nagoya University)

Nobutada Sako (Director, Satellite Systems Laboratory, Canon Electronics Inc.)

Table of Contents

I. Proposed MS Draft Goal Concept

1. MS Goals

1.1 The Name of MS Goals

"Achieve a society in which every person and Earth are connected to, coexist with, and benefit from outer space by 2050"

2. Targets (What Would MS Goal Achievement Look Like? What Would be Achieved by 2050 (and 2030)?)

By 2050, industrialization and commercialization of space technology will advance, and starting with cheap and small satellites, the era will shift from research and development of spacecraft to their production and personal use. Space components, such as propulsion systems and communication systems, will offer improved performance. Coordinated operation of large numbers of spacecraft in orbit will be possible, such as satellite groupings or multiple-craft formation flying. This will bring about a shift from launching spacecraft designed and developed for specific requirements (missions) **to using already-launched spacecraft by developing any necessary software for a particular mission and uplinking it.** (Figure1). This will be enabled through groundbreaking advancement in hardware as well as advanced interfaces. This will allow hardware to be developed separately from software, so that the hardware can be launched into orbit to await future software.

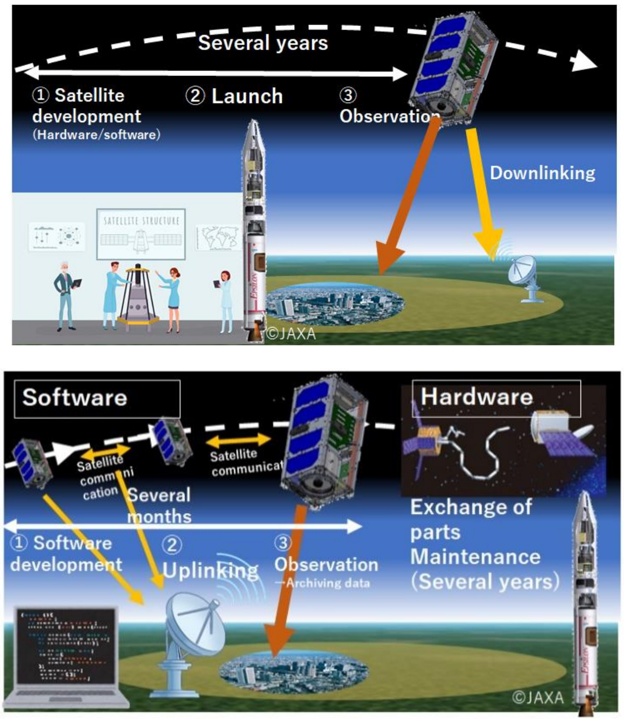

Figure1. (Top) Conventional spacecraft development. (Bottom) Spacecraft development in the proposed society.

Since development of hardware can proceed separately from development of software, hardware elements such as mechanical and electrical interfaces used in spacecraft systems will be highly standardized and unified at the component level for ease of development and launch. Spacecraft will acquire high precision and mobility through ongoing development of propulsion systems and high-precision orbital/attitude control technology. Spacecraft will no longer be launched anew for each mission, as previously. Instead, **anticipated changes in requirements will trigger a maintenance rendezvous/docking in orbit where relevant devices on the craft will be replaced to upgrade the hardware.** There will be spacecraft maintenance bases that replenish propellant and perform repair, making it possible to operate spacecraft in a manner similar to automobiles. Hardware will be reusable, so as to optimize launch count and quality to a high degree. In 2050, instead of the conventional approach, some hardware will already have been launched in anticipation of future use. The development approach will change as users and companies employing spacecraft in their business will focus on developing software.

As software development becomes the main focus, the mindset of **<u>"reconfiguring and sharing instead of rebuilding spacecraft"</u>** will take root. By sharing spacecraft, there will be more opportunities to try unprecedented ideas in outer space, and the preparation period will be greatly shortened. This should lead to explosive development and use of space technology. Furthermore, because spacecraft will already have been launched and their core operability proven, the main remaining task will be software development, dramatically reducing the risk of failure. Thus, it will be possible to escape from the **<u>all-or-nothing nature of current space systems, where a failure leaves one with nothing.</u>** We can expect that major new developments in space technology will follow.

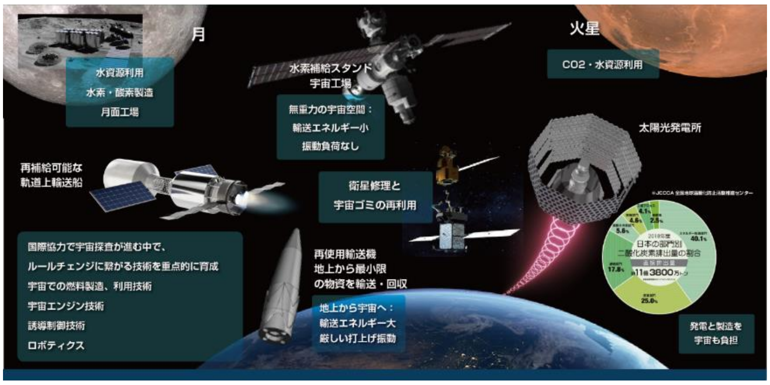

Figure 2. Transformation of space use through in-space manufacturing/consumption, and in-space manufacturing/terrestrial consumption.

The massive energy required to enter a low earth orbit from the ground is an obstacle to the use of outer space, requiring the development and use of massive rockets. When development can focus solely on software, there will be no need to embody it as hardware needing to be delivered into outer space. Software will be delivered as information, without mass, thus dramatically reducing costs. Instead of transporting everything needed from Earth to outer space, this way will minimize transportation needs and use materials on site to their fullest benefit. The idea of **<u>"finding or making what is needed in space instead of transporting everything needed from Earth to outer space"</u>** will branch out to become a mainstream view, to include in-space manufacturing and consumption of consumables, such as fuel, in space exploration. Since there will no longer be a need to transport everything needed from Earth, the new focus will be on how best to use the resources and energy available in the surrounding area, including thruster (specific impulse) fuel costs. Spacecraft are normally designed to withstand the severe load conditions experienced during rocket launch. In this new era, raw materials will be transported from the ground using reusable rockets, or found on the Moon's surface. Spacecraft will be built in space using 3D printers[1] or the like, with simple designs having no excess structures, further stimulating the use of outer space.

In-space manufacturing and consumption will be further developed. With the idea of in-space manufacturing/terrestrial consumption, in which electric power generated through space solar power generation[2] and products manufactured in space factories[3] are consumed on Earth, outer space will become essential for humans in both the energy and environmental spheres. Figure 2 is a conceptual view of this future.

Based on the two new ideas discussed above — **<u>"reconfiguring and sharing instead of</u>**

rebuilding spacecraft" and **"finding or making what is needed in space instead of transporting everything needed from Earth to outer space,"** people's daily lives will change to one **"connected with outer space**." The current space system is extremely rigid, with clearly defined main missions and anything unnecessary stripped away. In 2050, some playfulness and waste will be accommodated. For example, the bar for trying something new in scientific research will be lower, which may allow for accidental, unexpected, and new discoveries. The importance of trying something on a whim in outer space will be acknowledged. For example, new values may be created and new cultures built, from recreational and entertainment offerings such as product commercials, shows featuring the night sky[4], sports[5], and races, all the way to spacecraft designed as art pieces[6], satelloids with personalities, etc. There will be opportunities for people to gain new ideas through space. Furthermore, a shift to software-based development gives access to and use of spacecraft to more people: outer space will no longer be limited to experts. Disputes between nations on the use of space will be resolved, and people will be able to benefit from space technologies regardless of their nationality.

In a society such as this, where many people utilize outer space, the **"perspective from outer space"** will become even more important. Since a large number of spacecraft will be orbiting the Earth, bearing purpose-built software, space data will no longer be acquired only on an ad-hoc basis. **Ground and space will be continuously observed before a mission begins, with the results stored in the cloud in orbit,** so that data is always available in orbit. Instead of downlinking everything through limited communication, past observation data that was continuously observed and archived in orbit can be acquired from a spacecraft as needed, allowing for the use of space data and remote sensing on a global scale that is freed from temporal and spatial restraints[7]. This makes it easy, for example, **to verify the course and consequences of a disaster by reviewing the past data accumulated on a spacecraft after a disaster.** Not limited to the past, it allows for forecasting of global environment and human activities, which in turn allows measures to be taken to address environmental and other problems associated with the progress of scientific technology before they happen instead of after the fact, which is the case at the present. As such, **the use of space data beyond the conventional space system will become possible both in spatial and temporal scales.**

As the connection with outer space becomes stronger, the idea of **"coexisting with outer space"** will take root. Instead of launching an entire spacecraft as we do now, goals can be achieved simply by transmitting the information called software, along with launching limited hardware components. In this manner, instead of transporting everything needed from Earth, the mainstream idea will be to transport the minimum amount of materials while utilizing the materials on site as much as possible. For example, to build a base for exploration and other activities on the Moon or Mars, instead of bringing all the materials and energy from Earth, the focus will be on procuring such materials and energy on site. As the idea of in-space manufacturing/in-space consumption becomes mainstream, whether or not fuel can be procured in the local area will become important, in addition to the efficiency of the conventional engine in the transport system. For example, hydrogen and oxygen for a propellant can be manufactured from water on the Moon. On Mars, in addition to water, carbon dioxide can be used[8]. Various buildings and devices can be manufactured from rock as well. Furthermore, when bases for activities on the Moon and Mars have been built, the concept of in-space manufacturing/terrestrial consumption will take root, through which materials produced in outer space will be transported to Earth. Conventionally, resources and energy are circulated on Earth, but this new line of thinking opens up the circulation of materials on Earth to outer space, spreading the concept of actively using a circulation system that includes outer space.

With two changes in the rules — **"reconfiguring and sharing instead of rebuilding spacecraft" and "finding or making what is needed in space instead of transporting everything needed from Earth to outer space," spacecraft and the space system are no longer owned by individual organizations for different purposes but shared by society, becoming a social system**. With such changes, by 2050, outer space becomes a public space that various people can freely try using, leading to "a society in which every person and Earth are connected to, coexist with, and benefit from outer space" based on "connection with outer space," "perspective from outer space," and "coexisting with outer space."

3. Reasons for Setting MS Goals and Social Significance of Achieving Goals

3.1 Why Efforts To Set and Achieve MS Goals Are Necessary Today

Though outer space is still quite out of reach for most of society, anticipation for the new frontier is high. In order to lower barriers to outer space, space systems such as small satellites and low-cost/reusable rockets are being studied, and new space business that utilize these systems has begun. Presently, there is competition among the US, Russia, Europe, China, and Japan as new players come on the stage. There is even an estimate that by 2040, space business will triple in the international market[10]. On the other hand, as IoT, cloud, blockchain, and AI develop dramatically, spacecraft continue to use electronics and information processing system from a generation before. This is because the space system is characterized by unique environmental conditions, such as radiation and nonrepairable systems, which makes it difficult to introduce new technology, so mature technology is preferred. As such, though anticipation for outer space is high, disparity compared to the technology used in terrestrial settings is growing[9].

In order to utilize outer space as a society, obstacles must be removed, and new space engineering based on innovative thinking is necessary. The country that is able to transform the space system and its use will likely take the lead in the future. Therefore, it is important to propose and introduce a new framework of space technology now, promote research and development, and lead toward industrialization and commercialization.

3.2 Social Significance of Achieving Goals

In the pre-2020 conventional system, many spacecraft were designed and developed only once a need arose. The initial operation (setup and test run) was run to optimize the spacecraft. Then finally, data could be acquired. Specifically, standard-sized satellites are developed over a long period of time, and in the worse-case scenario, failure with launch or initial operation prevented acquisition of data. As a result, development of space technology has been slow. Under such circumstances, in order to respond to the social demand, research and development have been in progress toward shorter development time and real-time reaction, such as instant observation satellites. This led to the idea that development and launching of spacecraft are essential. The presently proposed society aims to see two major rule changes — **"reconfiguring and sharing instead of rebuilding spacecraft"** and "**finding or making what is needed in space instead of transporting everything needed from Earth to outer space"** — toward a major transformation in space technology.

In this future society, development and launching of spacecraft is no longer essential, and goals are immediately achieved by uplinking software. New technology can be tested easily and quickly, and data can be acquired. Explosive development in technology and use is anticipated.

Immediately achieving goals by uplinking software leads to a new **"connection with outer space"** in society. What appears to be a "wasteful" attempt can open up new values and build a new culture. Furthermore, by transitioning to software-based development, many people can access outer space, and international disputes regarding outer space will be resolved. In this way, people can benefit from space technology regardless of their nationality.

As increasing number of people will be able to use spacecraft and fields of study using remote sensing that observes Earth from outer space and data will become more active, leading to a new **"perspective from outer space."** Instead of acquiring data in outer space after a mission has begun, Earth and outer space will be continuously observed before any mission begins, allowing for new on-demand space data and remote sensing on a global scale with no spatial or temporal constraints. This fundamentally changes the method of information acquisition and research, leading to transformation in not only disaster but also in remote sensing[11] for land management, forest management, water resource management, and food security, and various fields of scientific observation, such as astronomy and meteorology. Its achievement not only leaves a major impact in the field of space technology, but also in various fields of scientific observation, such as remote sensing, astronomy, and meteorology, by accessing a data cloud in orbit.

In software-based spacecraft development, the idea of in-space manufacturing/in-space consumption, in which goods are procured on site, will take roots. This activates technological development that uses the energies, resources, and space found in outer space, leading to an idea of in-space manufacturing/terrestrial consumption where materials produced in outer space are used on Earth. With new ideas such as in-space manufacturing/in-space consumption and in-space manufacturing/terrestrial consumption, a path opens toward a new circulation system for resources and energy, creating a society based on **"coexisting with outer space."** Though it has been considered within a terrestrial circulation system, with the new ideas, the circulation system can be considered as a system that is open to outer space. This gives options with which a sustainable and rich society can be achieved with a framework beyond Earth.

By building a framework with which society can connect with outer space, major changes will take place in life, perspective, and circulation. By 2050, outer space will be a public space various people can freely try using within free time and space, leading to a new society based on space technology.

3.3 Outline of Efforts by Society as a WholeToward Achieving MS Goals

In the present research proposal, two major rules are changed — **"reconfiguring and sharing instead of rebuilding spacecraft" and "finding or making what is needed in space instead of transporting everything needed from Earth to outer space"** toward dramatic transformation of space technology. To achieve the proposed society, outer space; i.e., a space shared by the whole humanity, is utilized; thus, in addition to technological development and industry-academia-government collaboration in Japan, cooperation with other fields and countries become necessary.

In terms of technological development, functions of spacecraft subsystems — propulsion systems, communication systems, and information processors — need to be improved, and difficult challenges such as mass production of spacecraft must be resolved. Therefore, gathering of wisdom from universities, research facilities, and company researchers is essential.

In regard to cooperation with other fields, for example, world-class knowledge and technology used by the automotive industry, such as mass production and lean development, need to be actively and flexibly incorporated into the field of space. Furthermore, achievements from chemistry and material science will be useful. In this manner, Japan is well positioned toward the proposed rule changes, approaching the ideal society in 2050. Small-scale new players in the field of space, including small- to mid-sized businesses with production technology supporting the new space industry, become important as well. In the presently proposed society, every person has a connection with outer space. As humans expand their range of activities to outer space, ethical education and fostering of values also become important.

In terms of international cooperation, sensitive international issues, such as resource collection from other celestial bodies, will be handled. For the peaceful use of outer space stipulated by the Outer Space Treaty[12], not only technological cooperation but also international cooperation on legal systems and each country's approach becomes vital.

4. Changes in Social and Industrial Structures Stemming From Goal Achievement

In the proposed society, as long as there is the money to lease a spacecraft and knowledge of software, one can easily use outer space without knowledge of hardware specialized for spacecraft. This eliminates the disparity in space use as people from various countries and fields can access outer space. In this manner, a space use industry that is based on the leasing of spacecraft and data usage, spacecraft manufacturers producing hardware and software will see growth. Specifically, data from outer space can be correlated with ground data to provide solutions for challenges in various fields, contributing to stronger competitiveness in many industries.

As the social structure changes and the benefits of space technologies are enjoyed by many countries regardless of the country's level of science and technology, the number of people involved with outer space will dramatically increase. This will generalize the objective viewpoint of Earth from outer space[13]. Furthermore, since what appears to be wasteful will be allowed, new uses of outer space for arts, culture, and leisure will be discovered, deepening the global understanding through outer space and sharing values.

Once the stage of in-space manufacturing/terrestrial consumption is reached, in addition to the space transportation industry, diverse industries, such as energy sector industries that utilize outer space and the surface of the Moon, environment sector industries, and manufacturing sector industries will be born, leading to a transformation in social and industrial structures. Outer space will become essential for human activities, arriving at a time when outer space takes a root in social lives.

II. Statistical and Comprehensive Analysis

1. Challenges and Responses Needed to Achieve MS Goals (Scientific/Technological and Social Issues)

As people are newly connected with outer space and gain perspective from outer space in their daily lives, in order to know Earth more and build a society with a circulation system with outer space, the following challenges in the fields of science, technology, and society must be resolved.

①Challenges with science and technology

Figure 3 shows technological challenges that are important for "connection with outer space," "perspective from outer space," and "coexisting with outer space" that are in turn important for the proposed society. For "connection with outer space," technology that is able to reconfigure hardware based on software becomes important. To update hardware, standardization of interface, formation flight technology, docking, and construction technology for space structure become important. For "new perspective from Earth ," information processing technology, formation flight technology for multiple spacecraft, and user-friendly interfaces become important. For "connection with outer space," technology that effectively utilizes resources on site to support in-space manufacturing/in-space consumption, technology to obtain propellant on site, propellantless propulsion (use of Earth's and other planetary magnetic fields and interstellar medium), and robot technology via remote operation are needed. Associated research fields such as high-performance propulsion technology, cryogenic liquid propellant management technology under microgravity, and storage technology for cryogenic propellant such as liquid hydrogen become important. WG in the Figure indicates target WG for MOONSHOT, and there are fields that are developed alongside this.

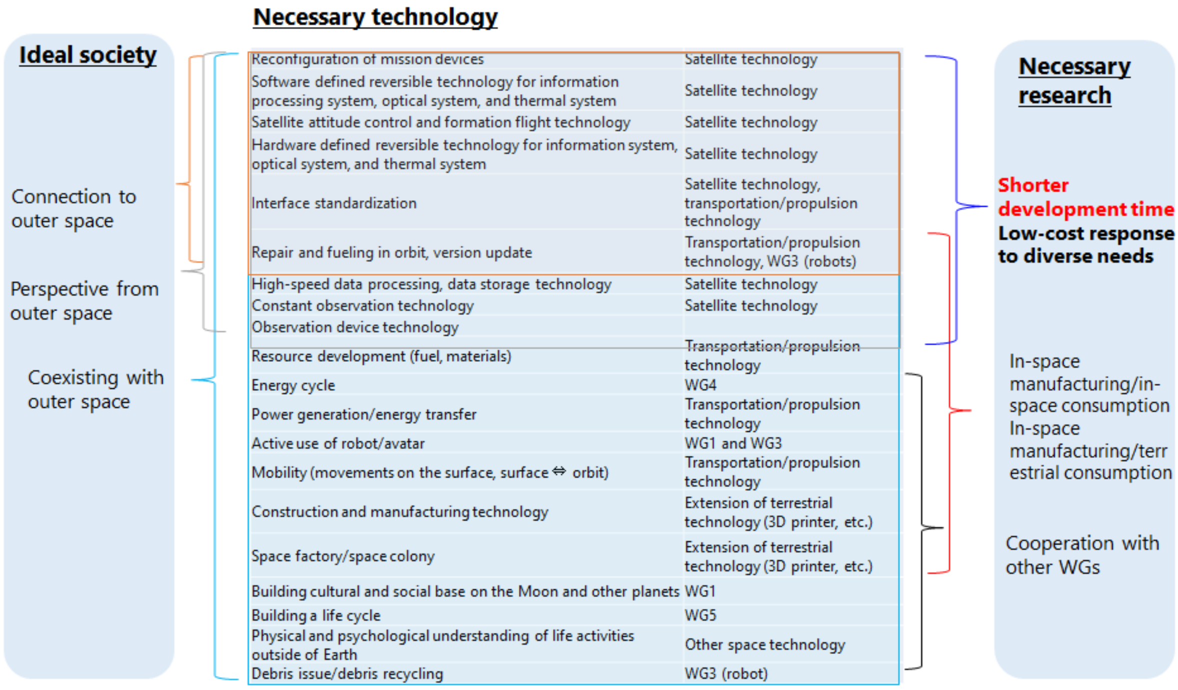

Figure 3. Technology necessary to reach MS goals.

②Social challenges

As many people shift their area of activities to outer space, and space industries and businesses become popular, various social challenges will arise. As outer space becomes commercialized, private laws, civil laws, the Space Law, and public laws on protection of personal information must be prepared. In the proposed society, since people from various countries will expand their area of activities to outer space, international decision is needed on a framework for the balance between increased activities and regulations. As activities expand to outer space, ethical education and fostering of values also become important. In terms of international cooperation, to achieve the peaceful use of outer space stipulated by the Outer Space Treaty, international cooperation based on the international governance on frequency of radio waves, useful orbital resources such as geostationary orbit, and space resources from other celestial bodies is necessary.

2. Overview of Research and Development Necessary to Achieve MS Goals

In the proposed society, development of spacecraft and technology to transport spacecraft to the target orbit become important.

For spacecraft, technological development polarized between smaller and distributed type and larger and high-performance type are anticipated by 2050[14]. Spacecraft based on highly-precise and large-scale space structures, spacecraft that consist of constellations of small satellites, and spacecraft to address the associated debris issues are being assumed. Specifically, since around 2000, development of small space applications such as small satellites became active. Furthermore, studies were conducted on new space use with multiple highly-accurate and high-resolution devices. The challenges are how to develop spacecraft at lower cost in shorter time, and how to shorten the development time for short-term development satellites. For new missions, it has been recognized that securing of a method to launch spacecraft into outer space is a hurdle, and efforts to address it have been made. Spacecraft that can support new types of missions, such as low-cost short-term missions by multiple spacecraft, and missions for high-resolution imaging, is desired.

For transportation, work has begun to find ways to lower fuel consumption and costs in order to transport observation devices and mission devices to the target location at low cost. In recent years, work has focused on the research and development of a reusable rocket that transports from the ground to a low earth orbit at a low cost[14]. Research and development assume that all fuel to travel from the low earth orbit to the geostationary orbit, the Moon, and planets is brought from Earth. Thus, fuel economy (specific impulse) is an important index. A space system that is able to transport to the target site at a lower cost and less fuel is desired. Furthermore, when it becomes possible to manufacture propellant on the Moon and Mars, technological research on long-term storage of propellant and supply becomes necessary.

Let us provide an overview on engines for outer space. Figure4 maps specific impulse (engine fuel economy) and output power (relative to thrust) for each type of engine. Conventional chemical propulsion covers a wide range of thrust, but specific impulse is low and fuel efficiency is poor. In addition to improving performances and functions of conventional rocket engines, there are innovative studies of chemical propulsion such as the detonation engine. Other parts of the Figure show electric propulsion, characterized by high specific impulse but low output; i.e., thrust. Engines that would fall in the right top part of the map, with high thrust and low fuel consumption, have not been achieved yet. Globally, studies of engines for outer space are focused in this direction.

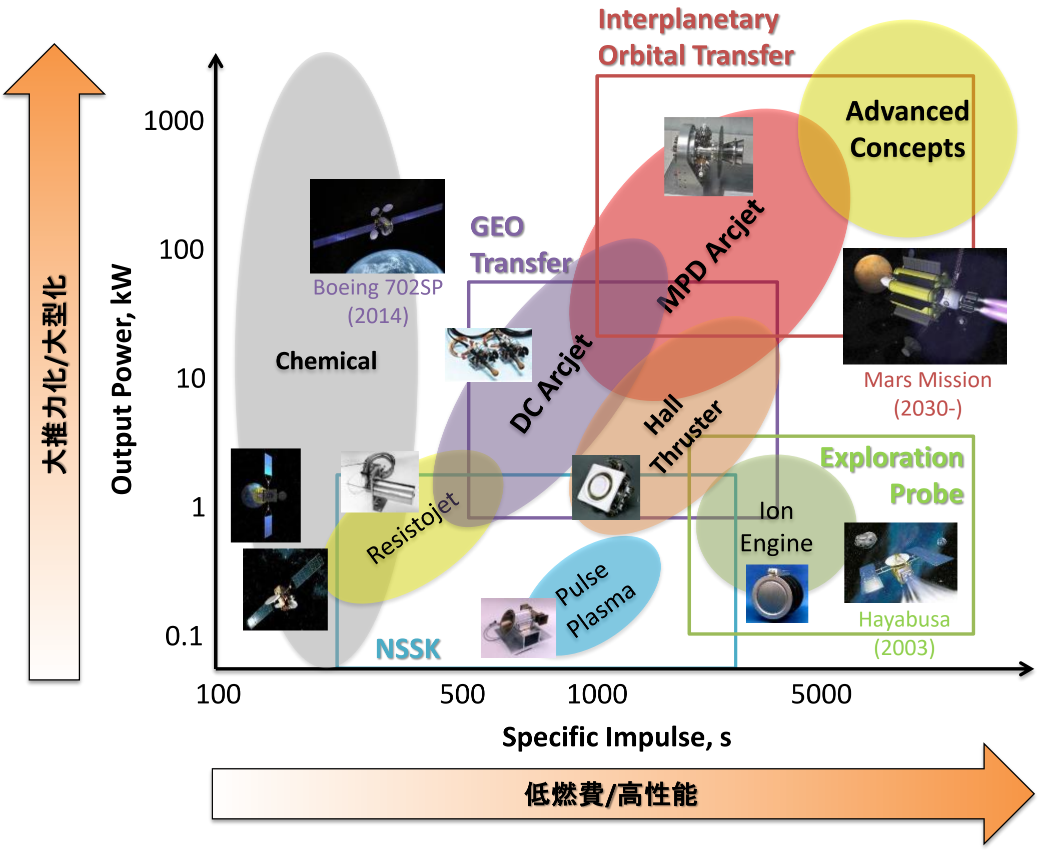

Figure4. Mapping of engines (Specific Impulse vs. Output Power).

3. General Research and Development Trends in the Subject Area, Overseas Trends in the Subject Area, and Strengths Japan can Offer

In order to reduce barriers to outer space, in recent years, the size of spacecraft is becoming smaller to reduce cost and development time. Notably, the percentage of small satellites that weigh 600 kg or less is rapidly increasing[15]. More than half of small satellites are American, followed by China, Japan, and European countries[15]. This is because the US and China have begun their businesses with small satellites. In Japan, commercialization is in progress with several venture companies, but not anywhere near the level of the US and China. However, among universities that are working on space engineering, two of the top 10 universities in terms of the number of small satellites developed are in Japan, as research and development at universities and research facilities are active in Japan[16]. As such, in Japan, research in space engineering and space demonstrations are quite active in universities and research facilities. Therefore, in Japan, there is a base to promote new ideas and to do research and development to reduce barriers to outer space, such as sharing of spacecraft. It is ready to be the first to demonstrate at universities and research facilities and pioneer new fields of research.

One concept associated with in-space manufacturing/in-space consumption that is presently proposed is in-space manufacturing. The number of patent application for in-space manufacturing is increasing[17]. The government funding for this area is especially increasing in the US[15]. As each country makes their efforts, as shown by Hayabusa 2, Japan is actively working on the propulsion system as an essential part of space exploration. For example, many Japanese universities are working on electric propulsion (plasma propulsion), such as ion thruster, which is the main propulsion system for Hayabusa and Hayabusa 2. Furthermore, the number of countries with technology to use cryogenic propellant, such as liquid hydrogen, that is the key to in-space manufacturing/in-space consumption is limited. This puts Japan at an advantage. Japan continues to develop and operate liquid hydrogen and liquid oxygen rockets, and along with the development of the latest H3 rocket, studies are being conducted on reusable rockets. Under such a circumstances, in-space manufacturing/in-space consumption needs to be further promoted based on the concept of "finding or making what is needed in space instead of transporting everything needed from Earth to outer space" with a larger framework of in-space manufacturing. New propellantless propulsion and solar power generation need to progress quickly, and related fields need to be enhanced.

III. Scenario to Achieve the Ideal Society

1. Fields and Areas of Challenging Research and Development Along With Research Topics

①Areas and fields to promote challenging R&D

Spacecraft that can support new types of missions, such as low-cost short-term missions by multiple spacecraft, and missions for high-resolution imaging, is desired. A space system that is able to transport to the target site at a lower cost and less fuel is desired. For the subsystem components of spacecraft (power supply, information processing system, communication system, thermal system, structural system, attitude control system, orbital system, propulsion system, and optical system), basic to applied research is desired on reconfigurable systems where structures can be changed after a launch. As for transportation systems, in addition to a low-cost ground to low earth orbit transportation system that reduces obstacles, transportation systems between orbits to contribute to in-space manufacturing/in-space consumption are necessary. For this transportation system, propellants that can be manufactured and supplied on the Moon and planets, such as those using hydrogen, oxygen, methane, and carbon dioxide, must be used. A high-efficiency propulsion system is essential. These propellants are loaded as cryogenic liquids or solids; thus, studies are needed to improve their storage and handling under microgravity, which is unique to outer space. As repair and part replacement in orbit increases, the durability to withstand several return trips between orbits is desired for engines. Wear to materials needs to be minimized, and technologies such as electrodeless discharge seen by the ion thruster of Hayabusa 2 and non-touch plasma cutters that utilize magnetic fields, are desired.

Considering that the developments are progressing rapidly in the US, Europe, and China, if research and development continue within the conventional framework, it is unlikely that the Japanese space technology would leave a mark. Thus, we aim for two rule changes: “sharing instead of reinventing the wheel” for spacecraft and “finding or making what is needed in space instead of transporting everything needed from Earth to outer space” for transportation to overturn existing ideas.

② Research subject for realization of MS Goal

To “sharing instead of reinventing the wheel,” it must be possible to change the configuration of spacecraft by uplinking from the ground. Methods to achieve such configuration changes are classified into the following three categories: Configuration changes by software, contactless changes by hardware, and contact-type changes by hardware. Contactless type changes do not require docking, assuming the addition of spacecraft to add functions to a group of satellites in formation flight. The cost increases from configuration change by software to contactless change by hardware and then to contact-type changes by hardware. However, notable changes to configuration become possible.

The following challenges with research need to be resolved.

1. Spacecraft reconfigurable by software

In-orbit changes to computing power of information processing system and data capacity (information processing system)

Software defined technology of communication system (communication system)

Changes to uplink that uses an interface by reconfigurable power source (power source)

Changes to solar absorptance coefficient α and infrared emissivity ε by uplinking (thermal system)

Changes to fuel consumption and time required by adjustments made to orbital and attitude control system (orbital/attitude control system)

Changes to the formation and constellation by uplinking (propellantless) (orbital system)

Changes to wavelength by uplinking and changes to resolution by super resolution (optical system)

Changes to message board (mission)

2. Spacecraft reconfigurable by contactless-type hardware

Functions added to or changed for a spacecraft formation by changes in the configuration of formation flight.

Functions added to or changed for a spacecraft formation by changes in the configuration of constellations.

3. Spacecraft reconfigurable by contact-type hardware

Addition of satellite parts as components on the orbit.

Reversible satellite configuration.

Addition, fueling, and exchange of satellite parts via docking.

Changes in the focal length of the optical system.

Interface standardization of components.

To “finding or making what is needed in space instead of transporting everything needed from Earth to outer space,” technological challenges associated with “in-space manufacturing” where resources and energy are acquired on site, “in-space consumption” that allows these items to be consumed, and “terrestrial consumption” where resources and energy obtained in outer space is consumed on Earth must be resolved. The following challenges with research need to be resolved.

1. In-space manufacturing

In-space manufacturing of propellant (manufacturing and storage of hydrogen and oxygen from water on the Moon and Mars, use of carbon dioxide from the Martian atmosphere, and synthesis of methane).

Use of the lunar soil as a construction material.

2. In-space consumption

Use of lunar and Martian resources as propellant (rocket and detonation engines that use hydrogen/oxygen or methane/oxygen, and plasma (electric) propulsion that uses hydrogen/methane/carbon dioxide).

Storage and supply technology of propellant on the Moon, satellite surface, and orbit.

Propellant use technology on orbit (liquid behavior control under microgravity, cryogenic thermal control).

Improved performance and longevity of engines (plasma control by combustion and magnetic field).

Propellantless propulsion (use of Earth’s and planetary magnetic field, space jet engine that uses interstellar medium such as hydrogen atoms, and use of attitude and orbital movement).

Use of He^3 on the lunar surface (fusion propulsion, electrodeless heating/acceleration technology for plasma by electromagnetic waves and magnetic field).

3. In-space manufacturing/terrestrial consumption

Space solar power technology.

Resource transportation technology from the Moon, Mars, and asteroids.

Manufacturing and transportation technology for heavy industry products in orbit, the Moon, and Mars.

2. Goals to be Achieved in 2030, 2040, and 2050 (milestones), Research and Development Toward Achieving Milestones, and Ripple Effect

1. The Year 2030: "Connection with Outer Space"

To achieve a society in which every person and Earth are connected to, coexist with, and benefit from outer space by 2050, first, the spacecraft system becomes reconfigurable so that technological demonstration becomes easy, technological advances are accelerated, and in-space manufacturing and commercialization are activated through the appearance of new players. By 2030, all spacecraft subsystems will have variable elements after the launch, allowing for people with different purposes to share a spacecraft. Laws necessary for space activities will be gradually updated, starting new businesses. This promotes industrialization of outer space, establishing diverse businesses.

2. The Year 2040: "Perspective from Outer Space"

With the industrialization of outer space, a large number of spacecraft are produced. The spacecraft system becomes more flexible and able to respond to diverse demands. Laws will be updated, and many companies will participate in space business, starting diverse services. On-demand perspective from outer space backed by a large number of spacecraft will be ensured. In this manner, many people can achieve perspective from outer space. Technological demonstration satellites and resource/energy exploration spacecraft will be launched to the Moon and Mars frequently.

3. The Year 2050: "Coexisting with Outer Space"

Under industrialization of outer space, industrial power of spacecraft and capital strength of space business lead to the formation of base on the Moon and even Mars. Businesses based on space solar power will begin on the Earth's orbit, leading to in-space manufacturing/in-space consumption and even in-space manufacturing/terrestrial consumption.

3. International Cooperation Toward Achieving the Goals

Instead of following the footsteps of the US, Russia, China, and Europe, it is important to find more important indicators by identifying new values and frameworks and changing rules. In this manner, Japan's contributions can be highlighted, and international trends in space technology be explored. In terms of spacecraft, it is important to interact with the rest of the world, such as in international standardization, by foreseeing future industrialization. In order to ensure opportunities to demonstrate space technology, overseas opportunities for launch pads for rockets should be actively utilized. To expand research achievements, international cooperation in technical demonstration and space science is necessary. To achieve the ideal society, international regulation on the governance of space activities is necessary. Specifically, cooperating with the US, Russia, China, and Europe is important.

4. Cooperation Between Fields and Sectors Toward Achieving the Goals

For "connection with outer space" and "perspective from outer space," autonomous robots developed through co-evolution of AI and robots in WG3 will play a major role. Furthermore, for coexisting with outer space, when building a society on the Moon and Mars through avatars, and examining resource circulation that considers outer space, cooperation with WG4 is expected.

5. ELSI (Ethical, Legal, and Social Issues)

(Ethical, Legal, and Social Issues in Efforts Toward Achieving the Goals and Solutions)

In the presently proposed society, everyone has a connection with outer space. Laws need to be updated considering that social activities will expand to outer space. Specifically, international public law that stipulates ownership of resources, energy, and areas of outer space between each country, and laws that straddle countries, such as international private laws, that stipulate solutions for accidents between spacecraft, will be necessary. Domestic public and private laws that stipulate application to launch spacecraft and renting systems in space business also need to be prepared.

In the presently proposed society, individuals can easily obtain information of various locations on Earth using remote sensing technology and so on. Thus, ethical education and fostering of values become important. As diverse people participate in a wider area of activities in outer space, one must question how best to strike a balance between increased space activities and rules and how space activities are governed.

IV. Conclusions

By 2050, industrialization and commercialization of space technology will be advanced, and the era of researching and developing spacecraft, such as cheap and small satellites, will shift to the era in which such satellites are produced for individual use. Repairing spacecraft and collecting and supplying fuel in outer space will be common, and combined with high-performance engine, free movement in outer space becomes possible. As various businesses begin, people's daily lives will change to the one with a "connection with outer space" through entertainment and so on. As spacecraft are mass produced, frequent observation from multiple points in outer space becomes possible, making "perspective from outer space" even more important. As the connection to outer space becomes stronger, the thinking of "coexisting with outer space" is born, promoting the use of resources and energy from outer space. To aim for such a society, in the present field of space engineering, two rules are changed: “sharing instead of reinventing the wheel” and “finding or making what is needed in space instead of transporting everything needed from Earth to outer space.” In this manner, we aim for a society in which every person and Earth are connected to, coexist with, and benefit from outer space.

V. References

[1] MadeInSpace, "FIRST COMMERCIAL 3D PRINTER IN SPACE", https://madeinspace.us/, (2021/7/7).

[2] 宇宙航空研究開発機構, "宇宙太陽光発電システム（SSPS）について", https://www.kenkai.jaxa.jp/research/ssps/ssps-ssps.html, (2021/7/7).

[3] Dan Gamota, "Manufacturing In Outer Space: Not Such A Far-Out Idea", Forbes, https://www.forbes.com/sites/forbestechcouncil/2021/05/06/manufacturing-in-outer-space-not-such-a-far-out-idea/?sh=2acc9e677ce8, (2021/7/7).

[4] ALE Co., Ltd., "TECHNOLOGY our satellite", https://star-ale.com/technology/, (2021/7/7).

[5] Space Future, "Space Sports", http://www.spacefuture.com/tourism/sport.shtml, (2021/7/7).

[6] Devon Van Houten Maldonado, "The artworks floating above the Earth", BBC, https://www.bbc.com/culture/article/20181214-the-artworks-floating-above-the-earth, (2021/7/7).

[7] Peter Bauer, Bjorn Stevens, Wilco Hazeleger, "A digital twin of Earth for the green transition", Nat. Clim. Chang. 11, 80-83, 2021.

[8] 宇宙航空研究開発機構, "日揮グローバルと月面推進薬生成プラント構想に係る連携協力を開始", https://humans-in-space.jaxa.jp/biz-lab/news/detail/001513.html, (2021/7/7)

[9] Chaim Gartenberg, "NASA’s latest Mars rover has the same processor as an iMac from 1998", The VEGA, https://www.theverge.com/tldr/2021/3/2/22309412/nasa-perseverance-mars-rover-processor-cpu-imac-1998, (2021/7/7).

[10] Morgan Stanley, " Space: Investing in the Final Frontier, Morgan Stanley ", https://www.morganstanley.com/ideas/investing-in-space, (2021/7/7).

[11] 4次元サイバーシティの活用に向けたタスクフォース, "4次元サイバーシティの活用に向けたタスクフォース最終報告書", 2018.

[12] 月その他の天体を含む宇宙空間の探査及び利用における国家活動を律する原則に関する条約, （1966年12月13日採択、第21会期国際連合総会決議2222号、1967年10月10日発効）, 1967.

[13] Douglas A. Vakoch ." Psychology of Space Exploration: Contemporary Research in Historical Perspective", Government Printing Office. ISBN 978-0-16-088358-3, 2013.

[14] 航空宇宙ビジョン委員会, JSASS 宇宙ビジョン 2050, 日本航空宇宙学会, 2020.

[15] BRYCE space and technology, “Smallsats by the Numbers 2020”, 2020.

[16] BRYCE space and technology, “Smallsats by the Numbers 2019”, 2019.

[17] Olivier de Weck, Afreen Siddiqi, Matthew Moraguez, Alejandro Trujillo, George Lordos, Mehak Sarang, "Commercial Space Technology Roadmap", MIT STRATEGIC ENGINEERING, 2018.