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Technological Evolution, Current Situation and Future Development of Space Colonies

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Abstract. Humanity's vision of space colonies-self-sustaining habitats beyond Earth has evolved from speculative fiction to a tangible frontier of scientific and engineering ambition. Rooted in 19th-century imagination and crystallized by 20th-century pioneers like Gerard K. O'Neill, early concepts such as the Stanford Torus and Bernal Sphere laid the groundwork for large-scale, Earth-like habitats in space. Yet, despite decades of progress, the realization of functional space colonies remains constrained by unresolved challenges: sustainable energy systems, closed-loop ecosystems, scalable material sourcing, and equitable governance models. This paper traces the technological evolution of space colonization, analyzing historical designs and their limitations while synthesizing breakthroughs in modern aerospace engineering—reusable rockets, 3D printing, nuclear fission, and emerging fusion technologies. And to explores how contemporary innovations address past shortcomings, such as replacing lunar resource dependency with asteroid mining or mitigating ecological fragility through hybrid energy systems and replace large-scale construction with modular design. Ultimately, the pursuit of space colonies reflects not only humanity's technological ingenuity but also its enduring quest to redefine the boundaries of habitation and survival beyond Earth.

Keywords: Technology Integration Strategy, Modular Space Engineering, Earth-Space Symbiosis.

1. Introduction

Space colonies, a type of human-engineered marvel of engineering currently existing only within science fiction, were first proposed within the scientific community in the 20th century. Their aim is to establish a space environment like Earth, suitable for human habitation, thereby becoming a popular solution for space migration. In 1969, Professor Gerard K. O'Neill of Princeton University formally proposed this concept [1]. Although this plan has never been implemented, it frequently appears in various science fiction works, such as Larry Niven's Ringworld. Today, after decades of technological development, space colonies seem not to be a distant fantasy but rather a potentially achievable vision. However, currently, there is scarce global summary and research on the concept of space colonies and the requisite technological foundations. This article will utilize chronological narration to provide a detailed compilation and discussion analysis of the origin of the space colony concept, an overview of its past development, the current state of existing technology, and future

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development pathways. at the same time, to a certain extent, analyse its potential future impact on Earth and discuss possible construction methodologies and the utilization of ecological and energy systems.

2. Early designs for space colonies

Space colonies are still in the idea stage, but there are still many scientists developing it. In a broad sense, a space colony is a very large, long-lived space station built in space that can cycle itself and does not need to rely on too much external energy. Such a super large space station can not only ensure that people inside have a real life on Earth, but also can directly observe the universe. However, before that, we need to discuss the ideas left by the predecessors to facilitate expansion and exploration.

2.1. Stanford torus

Stanford torus is a classic space colony design scheme jointly proposed by NASA and Stanford University in 1970. Its core goal is to simulate the gravity of the Earth through a rotating structure and provide a feasible framework for large-scale space habitation. From the NASA Technical report, we can get some basic information about the Stanford Ring, the shape of the Stanford Ring is composed of six modular pipes, each with a diameter of 15 meters, containing residential, agricultural and industrial areas. The exterior is covered with a two-meter-thick lunar soil layer, while the internal superconducting coils generate a Tesla magnetic field, which is used to shield cosmic rays, and embedded in titanium mesh to enhance the structure's resistance to micrometeorite impacts. Inside, it is connected by a central hub for docking spacecraft, research experiments, and microgravity industries (such as crystal growth).

At the same time, by rotating the ring body at a uniform speed of 1 RP, the gravity acceleration of 1g (9.8m/s^2) is generated in the outer circumference of the ring. Technologies such as reuse water recycling technology and waste utilization enable basic life support systems.

The primary energy source is solar energy satellites (SPS) for microwave transmission, and the backup energy source uses a nuclear fission reactor (U-235 fission) as an emergency energy source. Building resources are mined on the moon (aluminium, tita-nium, silicon) and transported to orbit using electromagnetic catapults. The address selected Earth-moon Lagrange point L5. The lunar soil is printed by 3D printing technology to reduce the dependence of prefabricated parts, which is the earliest blueprint for a cosmic colony [2].

2.2. Comparison of early space colony scenarios

Later, in Gerard K. O 'Neill's The High Frontier: Human Colonies in Space mention this space colony and two other derived space colonies, named Bernal Sphere and Island Three Cylinder, whose principles are roughly the same [1]. However, the differences in external acquisition and appearance are collated in the Table 1 below.

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Table 1. Key difference between three type of space colonies [1]

Dimension	Stanford Torus	Bernal Sphere	O'Neill Cylinder
Structure	Ring-shaped, 1.6 km diameter	Spherical, 500 m diameter	Twin cylinders, 32 km length, 6.4 km diameter
Population	10,000 people	10,000 people	Millions of people
Gravity Distribution	1g at rim, microgravity at hub	1g at equator, microgravity at poles	1g on inner walls, microgravity at axis
Energy System	Solar Power Satellites (SPS)	Mirror arrays + nuclear fission backup	Distributed solar + nuclear fusion
Internal Environment	Modular zones with linear agriculture	Layered habitats + polar agricultural domes	Simulated natural landscapes (mountains, lakes, cities)
Construction Complexity	Moderate	High (spherical stress)	Extremely high (structural stability)

From the perspective of that time, their Structure, Construction Complexities and Social Structures clearly showed a superior and subordinate relationship, but from the perspective of today, the modular design of the Stanford torus is more in line with current space station construction and development ideas, and the Bernal Sphere has been replaced by a newer design, Modified Kalpana One. Modified Kalpana One, proposed by NASA researcher Al Globus and his team [3], is a modified and simplified version of O 'Neill's cylinder, which has a much smaller population capacity of only 3,000 people compared to the millions of resident populations of O 'Neill cylinder. Due to its smaller size, its energy can be powered by the Stanford Torus orbiting Solar Satellites (SPS) plus the surface photovoltaic array. The building materials have also changed from the original lunar aluminium and titanium alloys to asteroid metals and carbon nanotube composite components that have already been mined, and the construction method has also adopted modular construction. The following two pictures show the comparison between Modified Kalpana One Figure 1 and the O 'Neill Cylinder Figure 2.

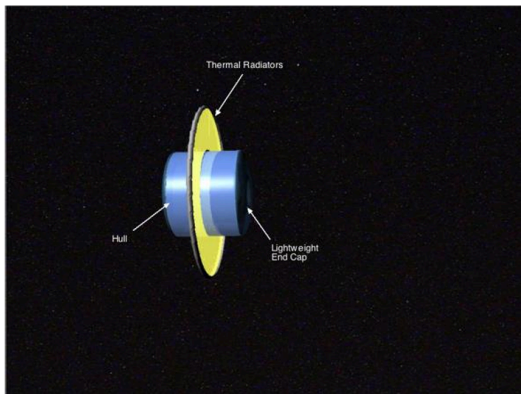

Figure 1. Modified simplified concept diagram of Kalpana One [3]

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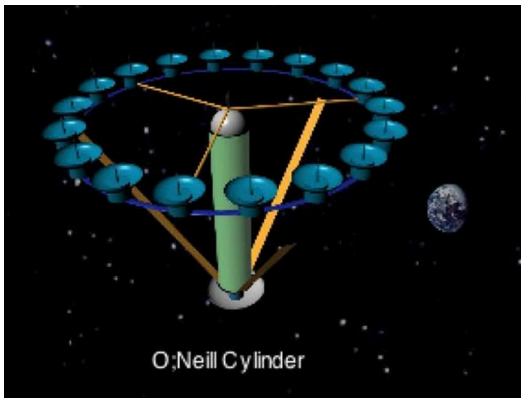

Figure 2. Conceptual simplification diagram of O 'Neill cylinder [3]

2.3. Shortcomings of the early space colony vision

Each of space colony also have its shortcomings, the Stanford Torus plan advocates mining aluminium, titanium and other metals from the moon [4], and plans to launch it to the Earth-moon l5 for assembly. However, from the current perspective, it is more convenient and convenient to use lightweight composite materials (such as carbon fiber, graphene) or 3D printing technology to use asteroid resources on the spot, although the total amount of iron nickel alloy in the moon is larger than the asteroid, but from the economic cost point of view, the cost of transporting lunar soil from the moon is far greater than the use of asteroids such as in-situ resources collection.

At the same tim2e, because the harm of nuclear fission reaction was not fully understood at that time, the problem of nuclear waste disposal and cooling in microgravity environment was not considered. therefore, there were too many expectations for nuclear fission reactions at the time. At the same time, although the Earth-moon L5 position can ensure the basic stable operation of the entire colony, some accidents may occur due to the harm of the solar wind and Jupiter vibration to the stability of the colony.

Modified Kalpana One as a modern design as well solves most of these problems, but there are still many unsolvable problems. For example, if the concentrated solar array is damaged due to space debris, the backup hydrogen energy is only enough to last 72 hours, if the energy cannot be restored, the radiation protection system may fail, and so on.

3. Modern space stations and technological innovations

This section will provide a systematic overview of the technological changes and evolution of the space station, as well as systematically organize and summarize the artificial gravity, closed-loop ecosystems and energy use and asteroid mining programs. In addition, it will highlight the interdependence of these technologies in shaping sustainable space habitation. Such an integrated perspective is essential for guiding future research priorities and longterm mission planning.

3.1. History of the space station

The Salyut I, launched by the Soviet Union in 1971, was the first space station to achieve a 23-day stay despite the failure of the reentry module, and the subsequent Salyut series was improved to achieve multimodule docking and cargo replenishment, laying the foundation for Mir [5]. Mir broke through the single-module limit, the first multimodule design to support flexible supplementary

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module [6], and its long-term life support system helped astronauts to create a record 438 days in space, marking the era of long-term human habitation in space. The International Space Station is jointly built by many countries, using a largescale modular structure, decentralized functions to meet the needs of various countries, and the introduction of regenerative systems (ECLSS) to reduce the dependence on Earth supplies. Its modular design significantly improves maintenance efficiency, verifies the feasibility of multinational collaboration, proves the long-term survival ability of human beings in space, and provides key technical support for the future vision of cosmic colonies.

3.2. Artificial gravity

During the Cold War period between the United States and the Soviet Union (1947 to 1991), Gagarin went into space for the first time in 1961, and people gradually found that long-term survival in the non-gravity environment in space was easy to cause muscle atrophy, bone loss and other injuries [7]. Therefore, the research on artificial gravity has entered a stage of rapid development.

It is imperative to note that artificial gravity is not a natural gravitational field. The most common method of achieving artificial gravity involves the rotation of a spacecraft or space station, thereby generating centrifugal force to simulate the effect of gravity. The magnitude of artificial gravity is contingent upon its rotational speed and radius and can be calculated directly using the centrifugal rate formula, as demonstrated in Equation 1.

$$F = m\omega^2 r \tag{1}$$

Artificial gravity currently has several benefits, such as providing an Earth-like gravity environment that maintains the relative health of skeletal muscles, while long-term microgravity environments tend to result in the upward transfer of bodily fluids, which can lead to facial swelling, nasal congestion and other symptoms, which artificial gravity can be a good solution to this point. But at present artificial gravity is still in the experiment, for example NASA uses centrifuges to perform artificial gravity experiments on mice and assess their effects on living organisms. NASA has employed centrifuges aboard the International Space Station to expose mice to various levels of artificial gravity (0 g, 1/6 g, and 1 g) to examine its impact on bone and muscle mass [8].

Artificial gravity currently possesses several substantial drawbacks. The primary concern pertains to the Coriolis effect, which manifests as space kinesiology and discomfort experienced by astronauts in rotating artificial gravity [9]. Recent studies have explored the potential resolution of this issue through the application of the dimensionless analysis method. This method utilizes a dimensionless parameter, such as the Rossby number, to assess the relative significance of the Coriolis effect [10]. The Rossby number is calculated using the equation 2:

$$Ro = \frac{U}{Lf} \tag{2}$$

The characteristic velocity of the fluid (U), expressed in meters per second (m/s), the characteristic length scale of the system (L), expressed in meters (m), and the Coriolis parameter (f) are the fundamental parameters in this system. The method entails determining whether the RO

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value must be solved and, if so, adjusting the size of U and L. Conversely, if the RO value does not require solution, it is simply ignored. Despite the apparent resolution of this issue, the Rossby number is confronted with numerous interference terms in practice, it will make the linear equation to the unilinear equation. A salient example is the construction of space colonies, where the bodies, even when constructed at the Lagrange point, are not completely stationary. This results in residual ac-celeration, which has a detrimental effect on the overall space station and potentially leads to the failure of the project [11].

In summary, the field of artificial gravity is currently undergoing long-term ex-perimentation. However, the calculation of the Coriolis effect Rossberg number is susceptible to factors such as residual acceleration, which hinders the attainment of the optimal solution. This phenomenon impacts the practical implementation of artificial gravity.

3.3. Closed loop ecological technology cycle

The closed-loop ecological technology recycling system, as the name suggests, can survive alone for a long period of time by relying on materials prepared in advance in a completely closed environment and without regular external supplies. The aim, of course, is to build an ecosystem that uses matter and energy efficiently and minimises waste emissions to support long-term space missions, with three main components: water cycle, air cycle and solid waste disposal.

The cycle of water resources depends on the body's own urinary and perspiration mechanisms. The waste, which contains a certain amount of liquid, is collected, filtered and purified for reuse, including water molecules floating in the air.

Air recycling is the photosynthesis of plants, and in the MELiSSA project, cyanobacteria (such as Arthrospira platensis) are used in the atmospheric regeneration part to convert carbon dioxide into oxygen through photosynthesis. Meanwhile, plant nutrients are made up of sunlight from the sun and carbon dioxide exhaled by astronauts [12].

There are two main ways to dispose of solid waste, one is to throw it into low Earth orbit and spontaneously combust in the atmosphere until it becomes ash. The second is to use the cargo ship and let the cargo ship transport itself back. Although these methods are environmentally controversial, they are by far the most efficient and cost-effective.

In summary, although the closed-loop ecosystem can achieve short-term self-sufficiency, due to the failure of the Biosphere 2 experiment, coupled with the current inability to achieve 99% energy conversion, energy loss is inevitable, so it needs to be sustainable through in-situ resource collection and replenishment.

3.4. Iteration of energy renewal

Early spacecraft relied on chemical fuels, which included both solid and liquid fuels [13], solid fuels such as solid propellants, and liquid fuels such as liquid hydrogen and liquid oxygen. These chemical fuels are mainly burned to obtain energy for launch and travel in space. Although the energy loss of chemical fuels is high but can get a strong thrust in a very short time, chemical fuels are still the first choice in the rocket launch stage [13].

Although chemical fuels are still used for propulsion, in space, early silver-zinc batteries and hydrogen-oxygen fuel cells have short endurance and low energy density. Can't sustain long-term space work [14]. Since the 1960s, people have gradually used more environmentally friendly, high-intensity solar energy instead. However, solar energy still has limitations, and in some extreme

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environments, such as planets too far from the sun, solar energy cannot be used for operation [15]. So, fuel cells are still needed as a backup energy source to make up for it.

At the same time, nuclear fission energy is also widely concerned. Its principle is to split the nuclei of uranium-235 and plutonium-239, so that they release energy [16], and then convert the heat energy into electricity, such as nuclear power plants and other facilities are through this way to generate electricity. Nuclear fission technology has been gradually applied to space operations, such as the United States "Kilopower" project,this is a relatively simple reactor designed by the United States for use in extreme environments such as the moon, Mars or deep space to power human habitats, scientific instruments and in-situ resource utilization (ISRU) systems, However, as mentioned in the Miao Liwei's study, the fuel for the Kilo power reactor was uranium-molybdenum alloy [17]. The fuel is slightly different from conventional nuclear fuel, table 2.1 shows the thermal conductivity and uranium density of UO2 ceramic fuel compared to uranium-molybdenum alloys at 873 degrees Celsius (Table 2) [18].

Table 2. Thermal conductivity and uranium density of uranium dioxide ceramic fuel vs. uranium-molybdenum alloys at 873 degrees Celsius [18,19]

	uranium dioxide ceramic fuel(Uo_2)	uranium-molybdenum(U-10Mo)
Thermal conductivity W/m·K	3.88	26.5
uranium density g/cm³	10.96	16.09

As the figure shows, conventional nuclear fuels, such as uranium dioxide (UO_2), have low uranium density and thermal conductivity. This results in instability that can be fatal in environments like space colonies. In contrast, uranium-molybdenum alloys have high thermal conductivity and density, which is beneficial for long-term, uninterrupted space colonization reactors. However, nuclear fission energy remains highly unstable. Nonetheless, its enormous potential cannot be ignored.

Compared with nuclear fission energy, nuclear fusion energy looks more practical, neither nuclear fission energy has such a high amount of radiation, but also has far more energy than nuclear fission energy. Fuel for fission energy, such as uranium-molybdenum alloys, is hard to come by. Uranium is scarce, but deuterium for fusion energy is endless. Deuterium is not difficult to obtain, if there is seawater can be refined, another resource tritium can be recycled through lithium. All these factors, nuclear fusion energy is undoubtedly the best choice for the future space field. But from the current point of view, whether it is the need to maintain the stability of hundreds of millions of degrees of hot plasma, or the existing fusion device is too large, it is currently unable to achieve the use of this energy for spacecraft. However, currently controlled nuclear fusion technology has been developing rapidly. Ding, S., et al. A Tokamak plasma state with high density and high constraint to achieve fusion energy is found in the study [20]. This indicates that more energy can be used to maintain the continuous progress of nuclear fusion reactions and converted into usable electrical energy, thereby improving the energy output efficiency, to achieve long-term energy conversion of nuclear fusion and reduce energy loss.

From today's perspective, none of the existing energy sources can complete the mission of perfectly replacing another type of energy, so on the space colony, each energy source should have, and in their own good position, to make up for the limitations of all energy sources and play their advantages.

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3.5. Asteroid mining program

Before Mars and Jupiter, there was an asteroid belt with many valuable mineral resources. These are naturally ideal as sources of materials for space colonies and Mars/moon bases. As a result, Nasa, the Chinese Space agency, the Japanese Space Agency and many other countries and companies want to mine these asteroids. At present, Japan's Hayabusa-2 spacecraft and NASA's Spirit probe have launched missions to explore asteroids. So far, according to Wang,W.et.al, the samples brought back all show that the asteroid has a very high mineral content and water content, which is extremely valuable for mining [21]. This indicates that the first space mineral resources planet bases can be built using the minerals to achieve the purpose of local materials.

4. The development and technological innovation of commercial spaceflight

This section will evaluate the status of technology accumulation and development of existing space stations and private enterprises (e.g., SpaceX, Blue Origin, etc.). this part will also analyse the potential benefits of this technology for space colonies. Additionally, it undertakes a thorough examination of the prevailing challenges confronting contemporary technologies, including the development of recyclable rockets, the integration of 3D printing technology, and the formulation of commercialization models.

4.1. Status Quo of technology accumulation of existing space stations and private enterprises

With the continuous deepening of space exploration, existing space stations and private companies such as SpaceX and Blue Origin have accumulated rich experience in the field of space technology, which has laid the foundation for the construction of future space colonies.

The International Space Station (ISS), an important platform for long-term human presence in space, has been in orbit for more than 20 years. It has accumulated a lot of experience in space life support systems, microgravity scientific research and international cooperation models. However, the technological development of the space station is mainly focused on short-term stays and scientific research, and there is limited support for the long-term self-sufficiency required for the construction of space colonies.

In contrast, the rapid development of private enterprises in the field of space technology has brought new hope for the construction of space colonies. SpaceX's Falcon 9 rocket has significantly reduced the cost of space exploration through multiple successful recoveries [22]. Its starship project is seen as a key technology for future Mars colonization, its iterative speed and innovative spirit have injected new vitality into space exploration. Blue Origin focuses on the development of suborbital vehicles and heavy lift launch vehicles, with its New Shepard and New Glenn rockets demonstrating their potential in reusable rocket technology [23].

4.2. Recoverable rocket

Recyclable rocket refers to the recovery and reuse of the first-stage rocket or booster through specific technical means. The inability of early rockets to be recyclable leads to the extremely high cost of single-shot rockets. The advantages of recyclable rockets are reflected in cost reduction and time saving. At present, Vertical landing technology is the mainstream of recoverable rockets at present, the concept is that the rocket stage after separation, through the engine reignition to adjust the attitude, using the grid rudder and thrusters to control the descent trajectory, and finally landed vertically on the land or sea platform

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Its recovery components are complete and can be reused very quickly [24], but it requires extremely long research, often requires the consumption of additional fuel, and requires strong thermal protection technology [25], the design is extremely expensive research and advanced talent, but the threshold is too high.

Current recoverable rockets still have a certain cost, but vertical landing technology allows the cost of rocket recovery to be reduced to a new height, which may be the mainstream technology module for some time to come.

4.3. 3D printing technology

3D printing is a technology that builds three-dimensional objects by stacking materials layer by layer. Its manufacturing efficiency, design since.Due to its advantages in degree and resource utilization, it has become a key technology for space exploration and space colony construction. It is also a major breakthrough in cutting costs.

3D printing steps have a basic process: modeling - slicing - printing - postprocessing. The principle is to form a digital model first, then layered, the 2D cross-section is stacked, and the resulting item needs to undergo a series of postprocessing, such as adding support structures and thermal protection [26]. Things like engines, lunar soil buildings, etc., can be synthesized and created by this technology. Through the article [27], I learned that the Archinaut One project has carried out a series of experiments on the use of 3D printing technology to manufacture larger structures in space than traditional methods in low Earth orbit, and I also learned that in 2023, The 3D printing equipment on the Tiangong Space Station uses a variety of materials such as plastic and metal for 3D printing to verify the printing effect of different materials under microgravity conditions. These experiments can confirm that 3D printing technology can be used quickly in space. which creates good conditions for the expansion of cosmic colonies and can be forged directly without launching rockets. This is enough to prove the importance of 3D printing technology.

4.4. On the importance of business model to space

In addition to the above-mentioned technologies driven by the private sector, the private sector is also turning space into a commercial industry. As the Outer Space Treaty (adopted by the United Nations General Assembly on 19 December 1966) refers to "recognizing that the exploration and use of outer space, including the Moon and other celestial bodies, as the domain of space activities of all States, is in the common interest of mankind, irrespective of the level of economic or scientific development of States; This kind of exploration and utilization should become the "development scope of all mankind" "All state-owned space enterprises cannot obtain great profits, which also creates the expansion and exploration of private enterprises [28]. From the upstream rocket manufacturing, technical research, etc., to the midstream space maintenance, fuel refueling, and finally to the downstream space hotel, space experiments. At this point, a set of mature and efficient industrial chain has been completed.

Another advantage of the private sector moving into the space industry is that it will enhance all aspects of technology. If only state-owned enterprises or the government carry out space development, it will lead to the situation of “Inability to effectively break out of areas”, whereas the private sector will develop additional advantageous technological fields in addition to the basic science and technology for the sake of its unique advantages and profitability [29], which will combine to play a good role in the development of space colonies, thus leading to the rapid

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development of the space field. The combination of these technological fields will play a good role in the development of space colonies, thus contributing to the rapid development of the space field.

5. The future development path and social issues of the symbiotic relationship between space and earth

This section will examine the ramifications of space colonies on human society and the Earth. For example, to explain the changing of social class, to explore the mechanisms of symbiosis between Earth and space, including the concept of space manufacturing.

5.1. The impact of the rise of space colonies on human society

Due to the limitation of space resources, space colonies will not introduce too many people at the beginning. Therefore, it is inevitable that managers will prefer "useful" people [30], such as researchers, engineers, doctors, investors, etc. As a result, the new class system will elevate the status of these personnel, especially in space. This is bound to create a "space elite class", further strengthening the technocratic system, but at the same time, if there are too many space colonies, it is bound to have a strong impact on the class of Earth, because the more attention to the space race, the Earth's disadvantaged will become more disadvantaged, resulting in an increase in the Gini coeffi-cient.

5.2. Symbiosis model between space colony and earth

Manufacturing in space will reshape manufacturing on Earth, and when orbital factories are created in the future, the microgravity environment will bring a lot of convenience to manufacturing, especially in the production of ultrapure crystals, biological organs and other high value-added products. Take Redwire's research on "The Redwire 3D Bio Fabrication Facility (BFF)," a machine that uses 3D printing technology to print human tissue. “Utilizing adult human cells (such as pluripotent or stem cells), the system can create viable tissue in space through technology that enables it to precisely place and build ultrafine layers of bioink " [31]. This will make the industrial division of labour on the planet more focused on innovative design and consumption. At the same time, space manufacturing will also give birth to the asteroid mining industry, which will break the situation like the "rare earth monopoly" on Earth. At the same time, space colonies can also be used for research and use of heavy industry, to alleviate environmental pollution and other levels.

6. The selection and refinement of technology

This section synthesizes the technologies and applications described in the preceding sections and analyses their role for space colonies. It also envisions the construction processes required for space colonies.

6.1. Modular pipeline infrastructure system

For a mature, complex engineering project, it is necessary to create pipeline engineering, so as to make the process of giving resources simpler and more convenient. The technology here can be used for things like the recoverable rockets mentioned earlier. From a depth perspective, the use of electromagnetic launchers on the moon could also be part of the pipeline. So, in terms of creation, there are three steps:

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First, build the base space station at the l5 point of the Earth and moon in advance, and build a lunar base and mining site on the moon, where recyclable rocket technology can be used for further cost reduction. Due to the Moon's low gravitational coefficient, the escape velocity requirement from the Moon is also lower, and since the moon has no atmosphere, there is no need for additional thermal protection.

Secondly, asteroid mining is carried out at the l5 point of the Earth and moon. The use of in-situ resource acquisition reduces the cost of transportation compared with lunar resource acquisition, but because of the work in space, it requires higher technology. At the same time, a simple deep-space platform was built to collect materials from the moon. The lunar material is the main material, the asteroid material is the auxiliary material, and the auxiliary material is collected by the robotic arm of the space station.

Finally, an electromagnetic launcher was built on the moon and its launching infra-structure materials were used. According to the papers of William R. Snow and Henry H. Kolm [32], the lunar electromagnetic catapult used electromagnetic force to accelerate the launch of cargo from the lunar surface to the Earth-moon L5. Its transport cost is only one over sixth that of a conventional rocket. Due to orbital instability, high-precision materials need to be transported on recyclable rockets. With electromagnetic transmitters, fuel costs can be saved, thereby reducing long-term costs. This is a basic assembly line transport.

6.2. Energy use

For a space colony, many of the energy sources might be needed. However, if you look at the optimal solution, the combination of solar energy + nuclear fusion is undoubtedly the best, and both energy sources have the advantages of high-density energy and inexhaustible. For the current human, solar energy can indeed be widely used, access is not very difficult, but the access to nuclear fusion energy is very difficult, as mentioned earlier, nuclear fusion energy needs to maintain the stability of hundreds of millions of degrees of high temperature plasma, while the fusion device is too large, difficult to normal use. However, from this point of view, nuclear fission energy is still the only choice for the ground base, but in deep space, nuclear fission energy will cause a certain degree of pollution, so it is necessary to solve the problem of nuclear waste treatment and heat dissipation. But now, conventional hydrogen battery technology cannot produce sustained power generation, so nuclear energy must be used for space colonies. In the short term, small nuclear reactors are the main power generation technology, solar energy is the auxiliary energy, and hydrogen batteries are the backup energy. In the long run, small nuclear reactors can be replaced with fusion devices. The distribution of energy use will be solar to supply daytime base loads, such as lighting and temperature control; Nuclear power covers nighttime and energy-intensive industrial needs, such as metal smelting and water recycling; Hydrogen batteries cope with sudden power outages, especially during solar flares.

6.3. Processing and expansion of materials

For largescale infrastructure materials, it is enough to create traditional factories on the moon, but for some parts with very complex geometric shapes used in space colonies, 3D printing technology is needed to expand and derivative. At present, 3D printing technology can be used in the factory on the moon, although 3D printing technology cannot print the core device for the time being, but the core device can be transported to the moon and use the lunar soil to print the shell and the shell of the lunar factory, which can effectively reduce the transport quality of the rocket. At the same time,

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the future space orbit factory can also supply and process materials, so that the common connection of the Earth - moon - space colony can be achieved, so that the overall processing line is formed. The space orbital factory can either process and supply the space colony in its initial stage or choose to merge after the space colony is completed, so that the industrial chain of the space colony can be expanded and enriched.

6.4. Semi-closed loop ecosystem

It was previously mentioned that closed-loop ecosystems can achieve extremely high resource acquisition rates, but due to the existence of the second law of thermodynamics and the law of entropy increase, it is impossible to create a completely closed-loop ecosystem. So, our focus is not on creating a closed loop ecosystem that requires almost no outside intervention, but on simple, lowcost replenishment. According to Carrasquillo, R. L [33], we can learn that the current water recycling system of the International Space Station can achieve a recovery rate of 93%. On this premise, according to the article of Wang, C. et.al [34], it is concluded that water resources can be replenished by in-situ resources such as water ice replenishment at the lunar poles. In terms of gas cycle strategy, in addition to using cyanea as oxygen regeneration product in MELiSSA project mentioned earlier, plant aeration technology can also be used as the remaining supplement. Since nutrient solution and water need to be supplemented regularly to complete the remaining carbon dioxide conversion, thus breaking the complete closed-loop results.

6.5. Modular design

Modular design is done by breaking down complex system structures into independently operating and combinable modules [35]. Large frame design, on the other hand, refers to the construction of an entire building at once, e.g., a mixed-concrete building is one in which the overall frame of the building is constructed first and then the details are added. Although, for example, the O'Neill cylinder, Stanford circle are that the space colony is supposed to be a large frame design, but from the current research, the modular design of the safety, reliability in space is much greater than like the earth building large frame design. First of all, it is very important that the construction and deployment of the speed and flexibility of the large frame model not only requires in-situ utilization of extraterrestrial resources (ISRU), and at the same time, the construction of the skeleton during the period of time need to have a very high degree of control, which is extremely difficult to implement in practice, because if the operation is not easy to suffer from the asteroid impact, or by the planet's gravitational drag, even if the construction of the Lagrangian point is still with a high degree of instability. Even if it is built at the Lagrange point, it is still highly unstable. Modular design, on the other hand, allows for the construction of small structural modules on the moon or asteroids and then launching them into the Lagrange points, which makes individual structures mobile, and even if they are subjected to drag or impact warnings, they can be set up with emergency evacuation plans, which can lead to a break from the risk. The modular design also allows the colony to be expandable and adaptable so that when new areas such as habitation zones, industrial zones, or changes to existing zones are required, functional growth can be achieved by adding modules or moving them around [36], which is especially important in the ever-exploring space environment. Also, when a module is damaged, it can be replaced and repaired relatively easily without bringing the entire space colony to a halt. These advantages justify the modular design, but the large frame design is relatively resistant to cosmic radiation because it can resist radiation by laying down lunar soil as a

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whole [37]. Those two could be combined, for example, by designing modules that fit more closely into the mega-structure, thus providing more effective protection against radiation.

7. Conclusion

This paper provides an overview and discussion of the history of space colonies, the current state of available technology, and future perspectives and scenarios. Early space colony concepts from 1977 are summarized and described in detail, and modern space colony concepts are compared and analysed for their differences and advantages and disadvantages. This is followed by a discussion of the history of existing space stations and their associated research technologies and prospects. Modern private sector innovations are then analysed and the importance of the rise of the private sector is discussed and analysed. This is followed by a comparison of the advantages and disadvantages of the symbiosis between space and Earth, and a look at the possibilities for future development. Finally, all technologies are summarized, the usability of past technologies for space colonies is discussed, and a simulation path for space colonies is designed.

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