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In-situ construction method for lunar habitation: Chinese Super Mason

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ABSTRACT

Lunar exploration has become increasingly popular, and lunar habitation research must be a core focus during the exploration of the Moon. The lunar habitation research must mainly include architectural and structural designs built using suitable material-forming technology and construction equipment. To address these issues, Chinese Super Mason (CSM) was proposed. This technology is an autonomous robotic construction system that is capable of automated assembling on-site prefabricated multistructural bricks and arched segments. The compound fabrication system was composed of a six-axis robotic manipulator and a dry mixed autoclaving fabricator carried on an autonomous-limbed vehicle platform. The Xuanwu Station for the lunar habitation conceptual design was developed and intended for erection by the CSM. A case study was conducted in a 2.8 m-long, 0.8 m-wide, and 1.1 m-high open arched-formwork structure fabricated within 8.5 h on the Earth. In addition, the Xuanwu Station was evaluated using finite element analysis software considering the temperature, air pressure, and other special environments on the Moon. The reliabilities and limitations of the CSM method were analyzed. Finally, the applications of the CSM in the extreme environment of the Earth and several improvements of the experimental equipment were discussed along with the proposed future applications for autonomous construction.

1. Introduction

Since the beginning of this century, the United States has restarted to explore Mars and even the outside solar system. In recent years, Europe, China, Japan, Korea, and India have been involved in the lunar exploration [1,2]. The lunar habitation has an important strategic value, such as the solar or nuclear energy supply, in the future, thus serving as a future space safety base and working as a platform for astronautic scientific research. Moreover, new special construction technologies and structures will emerge to support human exploration of lunar habitation construction under the extreme lunar environment, and existing engineering construction theories, methods, and techniques will be inapplicable in this situation [3–5]. Therefore, an autonomous construction method is bound to be the only effective means of building the lunar habitation in the extreme environment.

A 3D printing technology has experienced numerous applications in recent years, and many different scenarios have occurred in the construction schemes of lunar habitations for different research institutions [6]. The 3D printing technology applied to the lunar construction is difficult for several reasons. First, the material source must be considered and coordinated comprehensively to optimize material delivery. Second, the energy supply must be adequate to ensure that the components printed by the high-temperature sintering 3D printing technology can be perfectly implemented. The construction methods of the lunar habitation are mainly divided into Earth and lunar in situ construction. In terms of the Earth in situ construction, the University of Southern California, the National Aeronautics and Space Administration (NASA), and other institutions have proposed a method for transporting concrete from the Earth to the Moon and have used the “free-form additive construction system” and the materials from the Earth to print the structures [7]; for the lunar in situ construction, NASA has utilized BP-1 basalt regolith simulant and lunar basalt simulant JSC-1A as the building materials to produce large basaltic structures through high-temperature melting techniques [8]. The European Space Agency (ESA) [9] has proposed a particular patented 3D printing technology called D-shape. Considering its potential use for direct construction of complex structures and considerable dimensions, D-shape opens the possibility for exploiting in situ resources to build the lunar habitation using the Moon's rock powder as raw materials in the harsh environment of space [9]. In addition, a prefabricated brick assembly

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technology is applied to the lunar habitation construction.

Several researchers have aimed at using bricks as the construction components for lunar habitations. As an ancient construction technology, masonry has been studied extensively, from the previous simple load-bearing form to a recent complex system [10,11]. The brick assembly construction method applied to the lunar construction mainly focuses on two parts. The generation of machine code, process simulation, and robot control must be automated using an integrated design-to-robotic-fabrication workflow. The use of this workflow to produce complex tile patterns can be possibly installed economically and efficiently, similar to hand-based techniques, on various mathematical algorithms and image-based methods. Besides the complex systems are characterized by many independent components with low-level actions that produce collective high-level results. The basic structural units can be composed of ever-changing and multiple functional structures [12]. There has been limited research on the robotic prefabricated lunar soil brick assembly scheme has been applied to lunar construction. Huazhong University of Science and Technology proposed the autonomous robotic prefabricated lunar soil brick construction method for a lunar habitation.

The People's Republic of China has identified three phase objectives of the Chinese Lunar Exploration Program, that is, "winding, falling, and returning" [13]. These objectives refer to exploring abundant resources on the Moon for the future, expanding international cooperation in space, and realizing the space dream of humans. The continued pursuit of lunar exploration is the next step toward exploring the construction of the lunar habitation through autonomous robotic initiatives. Given the complex and uncertain lunar geological and environmental conditions, several most difficult challenges have emerged for the success of a long-term human settlement on the Moon [14]. Different schemes that can be selected and various architectural and structural designs are constrained by the extreme lunar environment. In addition, the material-forming technology and construction equipment contain numerous questions to be solved. We may have several methods to achieve our goal, that is, to design and construct a lunar habitation; these methods are difficult to compare with one another [15]. An autonomous robotic construction method for a Chinese lunar habitation is generally applicable and consistent with the requirements of lunar construction and can be developed through a careful comparative analysis of schemes. The main contribution of this research is to propose a new method for lunar habitation.

The remainder of this paper is organized as follows: Section 2 contains the related research for the construction environments and methods of the lunar habitation. Section 3 describes the method designed for requirements and the construction process of the lunar habitation. Section 4 proposes the structures that must be built for the lunar habitation called the Xuanwu Station from the aspect of architectural and structural designs. Section 5 presents the methods for building the station effectively through further analysis of material-forming and construction technology with the conceptual design of the Chinese Super Mason (CSM). Section 6 introduces the experiments performed to test the construction process in the indoor environment on the Earth and reports the obtained results. Section 7 provides the conclusions drawn from this study and suggests several ideas for future work.

2. Background

2.1. Extreme environments for lunar habitation construction

The complex environments on the Moon, including gravity, temperature, atmosphere, radiation, lunar regolith and dust, and moonquakes, must be thoroughly understood to ensure the normal construction and operation of the lunar habitation. The lunar environment will significantly impact the construction and operation processes of the lunar habitation. These environmental factors on the Moon can also be influential to the performance, reliability, and working life of the lunar habitation construction equipment and the lunar habitation itself. Thus, the lunar environment is of necessary concern and provides the study of lunar habitation and construction equipment design with a major constraint factor.

The gravitational acceleration of the Moon is one-sixth of the Earth's; gravitational acceleration is a key parameter that must be considered seriously. The mechanical properties of the lunar regolith must be considered when the foundation is designed. Furthermore, the actuation of power machinery on the Earth is different from that on the Moon. If the actuation is designed in accordance with the requirements for operation on the Earth, then the power machinery will not adapt to the requirements of the lunar gravity environment. The difference will certainly cause a mechanical overshoot, which will lead to equipment fault or damage [16,17].

The temperature difference between day and night on the surface of the Moon is extremely large. The maximum temperature during the day is nearly 400 K, and the temperature of the shadow areas is nearly 90 K. To resist the extreme temperatures on the Moon, a compacted lunar regolith layer is required to cover an entire structure. The thickness must be between 1 and 4 m based on the specific requirements of the lunar environment and the construction factors [18]. In the dark night on the Moon, the solar cells cannot work, and thus, maintaining energy is difficult for the battery. The temperature differential in various areas of the Moon makes the design, use, and maintenance of the equipment considerably difficult, and the adaptability to temperature is particularly important. Thus, the temperature is a significant factor.

The atmospheric density in the close space environment and the lunar surface environment is only $1/10^{12}$ on the Earth [19,20]. The lunar habitation must maintain a certain internal air pressure to support life systems. Another problem is the heat dissipation on the Moon. The two main heat dissipation modes, namely, convection and conduction to an atmosphere, are unavailable on the lunar surface; it can only dissipate heat by radiation, and the heat emission efficiency is much lower than that of an atmosphere. The vacuum environment on the Moon significantly influences the structural design of the lunar habitation and the heat dissipation, thereby making the selection of materials and the design of equipment difficult. Thus, the atmosphere is also an important factor that must be considered.

Other challenges for a lunar habitation with extreme environments must be considered carefully. The lunar radiation environment mainly consists of three charged particle sources, namely, solar wind, solar cosmic rays, and high-energy galactic cosmic rays outside the solar system. The habitation wall must be sufficiently thick to withstand the particles with a high concentration of electric radiation. Lunar dust can be considered moving lunar soil, which carries an electrostatic charge and has strong adhesion. In addition, lunar dust has a strong capability to corrode mechanisms, which carry electrostatic charges that can easily adhere to conductive surfaces that are ungrounded. Approximately 600–3000 moonquakes occur annually, and the intensity of these moonquakes is sufficient not only for shaking the habitation but also for making the hard rock layers on the Moon to continue to vibrate for several minutes; this phenomenon is unstable for the bases of the lunar habitation structure.

2.2. Design and construction methods for lunar habitation

A lunar habitation must provide protection against various hazards, such as extreme temperature and radiation. Different types of lunar habitation construction structures, including inflatable, rigid, and mixed structures, have been proposed. Inflatable structures demonstrate a rapid speed of construction, low cost, and effective support of the internal pressure load. Rigid structures are another type of lunar habitation structure, which uses lunar in situ resources as the basic material structures and the protective materials [21]. Considering that the necessary aggregate and cement for producing concrete are costly to

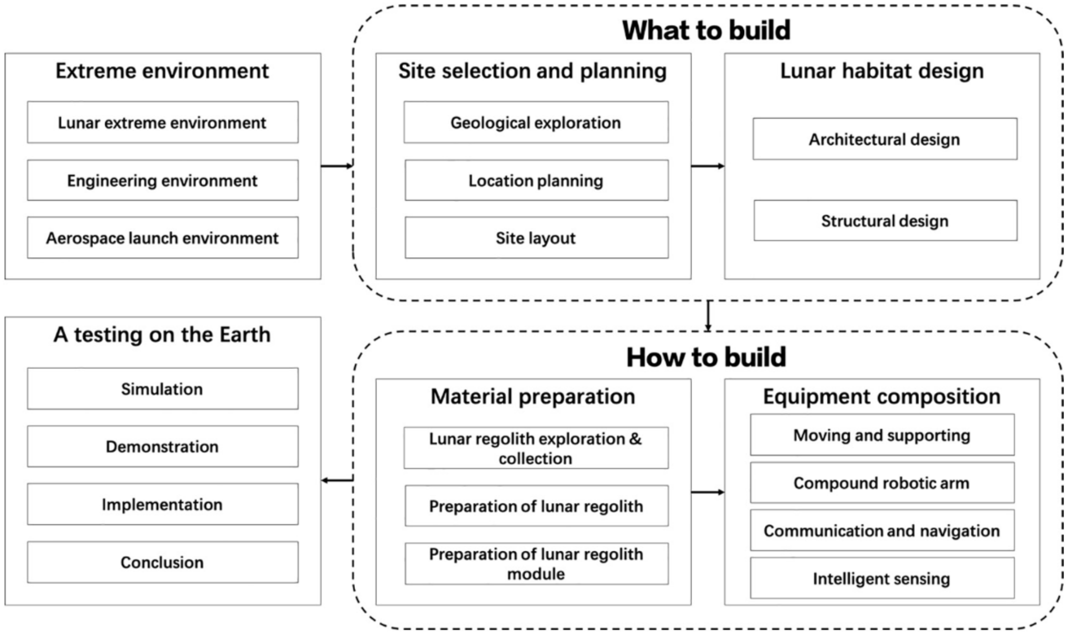

Fig. 1. Overall framework of the study.

transport from the Earth, in situ resource on the Moon is the development direction for building a concrete lunar base in the future [4,22,23]. Inflatable structures also have low internal space utilization and weak protection against small micrometeorite particles, whereas rigid structures do not have these problems. Thus, combining the two structural forms, that is, the mixed structure, will be favorable. Mixed structures have the efficiency of inflatable structures and the safety of rigid structures.

The construction methods, including the construction material from the Earth and the current lunar in situ construction technologies, are the prevailing path to lunar habitation construction. The first method is proposed for utilizing the construction materials brought from the Earth, tailored for low material demand and a growth-at-all-cost situation. Therefore, the lunar in situ construction is appropriate because it will have high material demand and human safety requirements.

For lunar in situ construction, several schemes, including the 3D printing and lunar brick construction technologies, can be used. NASA proposed to use a high-temperature sintering method, while the ESA proposed the "D-shape" 3D printing technology to build the lunar habitation using rock powder as raw materials. NASA's facility for Desert Research and Test Studies presented a mature system coupled with an additive manufacturing technology for fast and reliable printing of the lunar infrastructure [7,24].

A 3D printing lunar habitation using a high-power laser to melt the lunar basaltic surface layer into a glass-like material has also been proposed [8]. In addition, a 3D printer developed by the ESA using the "D-shape" technology was designed to use lunar basalt rock powder as the raw material and glue it to form a lunar habitation with honeycomb unit walls [9,25]. The lunar habitation construction is mainly based on the 3D printing technology. Several scholars have simulated lunar bricks to study the prefabricated structures of a lunar habitation. For example, a prefabricated concrete lunar habitation structure with a diameter of 120 ft and a height of 72 ft was proposed [26].

However, the 3D printing technology, compared with the prefabricated construction technology, exhibits several problems in the lunar environment. The maximum size of the lunar construction is limited when the 3D printing technology is compared with prefabricated construction, and the latter option can make large structures [6,27]. For prefabricated construction, when robots are executing work on the construction sites, they can go up the steps and continue to work. This technology is not limited by size. 3D printing requires continuous processing and construction. The one-time supply of material determines the size of the construction space. The prefabricated scheme is simpler and more flexible and convenient than the 3D printing technology. The components can be produced in advance and separately. The logistics are not very strict, and this scheme is easy and suitable for in situ construction. 3D printing is a technique in which a printing material is processed layer by layer [28]. Therefore, the 3D printing technology requires a flat field, and sometimes, it even requires ground processing. 3D printing demonstrates several other problems, such as high processing costs [29], low manufacturing precision [30], and high energy consumption [31]. To address the aforementioned various problems, the 3D printing technology and the superiority of the prefabricated construction must be considered collectively, rather than separately. Therefore, this study aims to clarify the problems caused by the method of masonry construction in the lunar environment and the difficulties and challenges that exist in the architectural design, structural design, and construction equipment.

3. Research approach

3.1. Overall framework

This section is dedicated to illustrating the design scheme and the techniques for building our lunar habitation through the autonomous robotic construction method in a lunar surface environment.

The six main steps for the lunar habitation construction methods are illustrated in Fig. 1. The first step is to comprehend the extreme environments, including the lunar, engineering, and aerospace launch environments. Subsequently, site selection and planning are performed to explore the geology, location, and layout of the site. The overall design plan of the lunar habitation is described from architectural and structural perspectives. The construction material preparation processes, including lunar regolith exploration and collection and lunar brick preparation, are explained in the fourth step. Once the construction technology has been determined, the building equipment is proposed on the basis of the moving and supporting device, compound robotic arm, communication and navigation device, and intelligent sensing device in the next step. Finally, the construction process is tested and verified under the laboratory conditions on the Earth on the

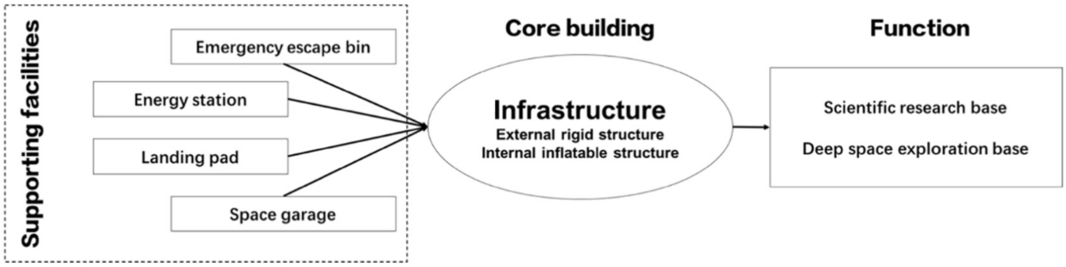

Fig. 2. Lunar habitation composition and construction goals.

basis of the abovementioned technology. Each aspect of the lunar habitation construction process is explained below.

3.2. Design requirement for the lunar habitation

The lunar habitation in our scheme consists of a mixed structural core building and several relevant supporting facilities to provide the logistics for space activities, as depicted in Fig. 2. The site area, which can be used by 3–6 people, is expected to be 100–200 m^2, and its service life is over 30 years. A significant amount of materials is ejected during spacecraft landing given the influences of low lunar gravity, and this condition requires a high impact performance of the lunar habitation made of lunar regolith. Therefore, the mechanical properties of the lunar regolith must be considered when designing the landing pad foundation or any berms to protect nearby habitations. A compacted lunar regolith layer must be mounted on the lunar habitation and be sufficiently thick to dampen out the lunar surface temperature. The solar energy and nuclear power must be used together in the dark night on the Moon because the solar cells cannot work, and carrying and maintaining energy are difficult for the battery. The vacuum environment significantly influences the structural design of the lunar habitation and heat dissipation. The lunar habitation must maintain a certain internal air pressure to support life systems, which demand the shear strength of the structure to be adequately strong. The structures of the lunar habitation can be designed in a modular form; thus, a standardized emergency escape bin and space garage can be assembled when they are required. The habitation wall must be sufficiently thick to withstand the impact of particles with a high concentration of electric potential and a contingency factor, such as moonquakes and micrometeorite impact. The lunar habitation design team is responsible for studying the architectural and structural forms, material mechanics, and equipment function under extreme conditions (i.e., gravity, temperature, atmosphere, radiation, and lunar dust) using 3D printing and robotic construction.

3.3. Robotic construction arm for lunar brick assembly

An autonomous robotic construction scheduling system is normally implemented to provide support to build several structures. For different application scenarios, the robotic construction system can be mainly divided into three categories, namely, gantry, unmanned aerial vehicle (UAV)-like device, and robotic arm. Each type has different advantages, disadvantages, and challenges in the construction process. The gantry system is generally simple to control and can carry heavy loads, such as large-scale fabrication lunar regolith modules. However, the operational flexibility of the gantry system is limited, which is especially fatal to produce complex components and work on the existing structures. Moreover, solving such problems as a collision with the structure and gantry scheduling is increasingly challenging. The UAV-like device, as an alternative to traditional scheduling mode, can conduct the motion characteristics of itself in a hover state and remote controls, thereby solving existing problems associated with conventional work platforms. A comparison determines the significant difference among the robotic arm, gantry, and UAV-like device under the extreme environments on the Moon and engineering objects. The robotic arm is a relatively improved method for the lunar habitation construction. We can utilize the precise control and stability of the robotic arm system, which can realize the multiple construction functions by integrating different tools in the end effector. In the robotic arm-based construction, further research is required to identify self-colliding situations and determine the lunar habitation construction technical requirements.

The robotic arm in this demonstration experiment is ABB IRB 6700, which consists of six axes (6 degree of freedom (DOF)). The coordinate system of the waist joint (axis 1) is regarded as the base coordinate system for the robot. The robot D-H coordinate systems of ABB IRB 6700 are established, as demonstrated in Fig. 3, using the standard D-H parametric method. The detailed D-H parameters in accordance with the physical robot structure are presented in Table 1.

After determining all the linkage coordinate systems, the relative relationship between adjacent linkages i and (i − 1) is represented by

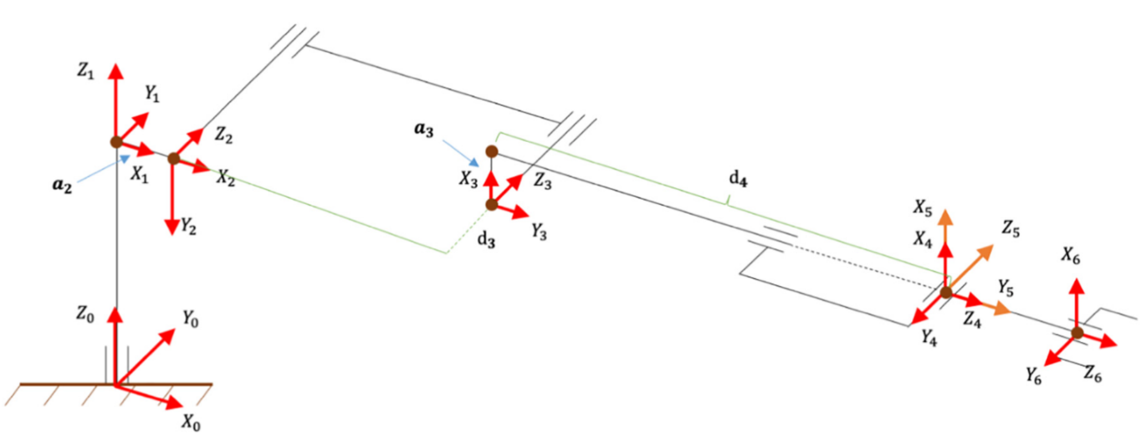

Fig. 3. Diagram of the D-H coordinate system of ABB IRB 6700.

Table 1
D-H parameters of ABB IRB 6700 (6-DOF robotic arm).

Linkage i	Joint rotation angle (θ_i)/(°)	Distance (d_i)/mm	Length (a_i)/mm	Twist angle (α_i)/(°)
1	0	780	320	−90
2	−90	0	1135	0
3	0	0	200	−90
4	180	1182.5	0	−90
5	0	0	0	90
6	0	200	0	0

Eq. (1). The parameters listed in Table 1 can be substituted in Eq. (1) to obtain the kinematic model of the 6-DOF robotic arm (Eq. (2)).

$$^{i-1}T_i = R_z(\theta_i)D_z(d_i)D_x(a_i)R_x(\alpha_i) = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$^0T_6 = {}^0T_1{}^1T_2{}^2T_3{}^3T_4{}^4T_5{}^5T_6 = \begin{bmatrix} n_x & o_x & d_x & p_x \\ n_y & o_y & d_y & p_y \\ n_z & o_z & d_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

This study focuses on the innovative robotic method of the lunar construction, rather than the mathematical model of the 6-DOF robotic arm; thus, the detailed mathematical identification and solution of the robotic arm are similar to the existing normal methods, according to References [32, 33]. The workspace of the robotic arm in the demonstration experiment is exhibited in Fig. 4.

4. Design of the Xuanwu Station lunar habitation

4.1. Architectural design of the lunar habitation

The conceptual design of the lunar habitation originates in the Basalt (Xuanwu in Chinese), which is one of the four divine beasts in ancient Chinese culture, with a shape similar to a black tortoise. Xuanwu symbolizes "Lao Yin" in the Four Quadrant, which corresponds to the Moon's Chinese nickname "Tai Yin." Basalt or Xuanwu is the officer that guards the four days of God; it is mainly used by the people as the town of spirits, which appear in the palace over the image, and the Dianmen gates to defend peace and tranquility. Therefore, we name the lunar habitation "Xuanwu Station." On the basis of the Xuanwu totem, the overall shape of the "Xuanwu Station" is summarized and condensed to form the overall outline of the building, and parameterization, modularity, and other techniques are applied to this design. The entire building is based on the arch structure, and the surface is decorated with a scale style, as displayed in Fig. 5. This type of architecture is regarded as a type of post-modernism and deconstruction, and we put this architecture as a new form of aesthetic style.

The core structure of the Xuanwu Station is an arch that consists of the archway and arch foot. The architectural design is conducted by considering the effect of extreme environments on the Moon and other functional requirements that are the essential parts of daily life for astronauts. In Fig. 6, solar-powered materials are used as the building facades and the decoration. In this design, the exterior facade of the building is not a traditional plane but is tilted and interlaced, looking as beautiful as the scale of a turtle from afar. The arched structure and external protection layer can be used to resist the lunar extreme environments in its stable structural form, radiation protection, and thermal insulation functions. We perform the interior virescence design using green plants to separate space and achieve different functions of the space, in which the layout must be applicable for the low lunar gravity.

In the conceptual design, another feature that is different from other lunar habitation designs is the standardization and extensible architecture. In Fig. 7, several of the standardized habitations connect with one another using a channel to form different clusters of settlements. The standardized and extensible architectural styles help improve the Xuanwu Station design by providing an enhanced organization of its elements, thus resulting in benefits, such as flexibility, extensibility, and maintainability. The lunar habitation design is a difficult and time-consuming task because the architect must handle conflicting factors and different ways to organize the architectural elements. Therefore, the advantages of this architectural style lie in the standardized lunar habitation, simple connectors, and rules on combining lunar habitations when an emergency or other situation occurs to use the parts that can be spliced.

4.2. Structural design of the lunar habitation

In this part, we will introduce a new conceptual structural design of an erectable lunar habitation using prefabricated building blocks made from the in situ lunar regoliths. The flank wall and foundation of the lunar habitation are fabricated by cubic blocks, among which a joggle joint is adopted. The roof is erected by arch segments with joggle joints, and a 2 m-thick lunar regolith layer is placed on top to shield the entire structure against the hostile environment. We design the structuring scheme of lunar regolith module arch, as presented in Fig. 8(a). The lunar habitation is 14.0 m long, 8.0 m wide, and 5.5 m high.

In terms of the environmental conditions on the Moon (one-sixth of the Earth's gravity, temperature variation of approximately 300 K within a lunar day, and frequent moonquake), the loads, which will be considered irregular on the Earth, are actually regular for our lunar habitation structure. To investigate the behavior of the structure under such extreme loading, a 2D numerical model is established using the finite element software, ABAQUS, for static analysis of the proposed lunar habitation, as illustrated in Fig. 8(b). A PE4 element (four-node

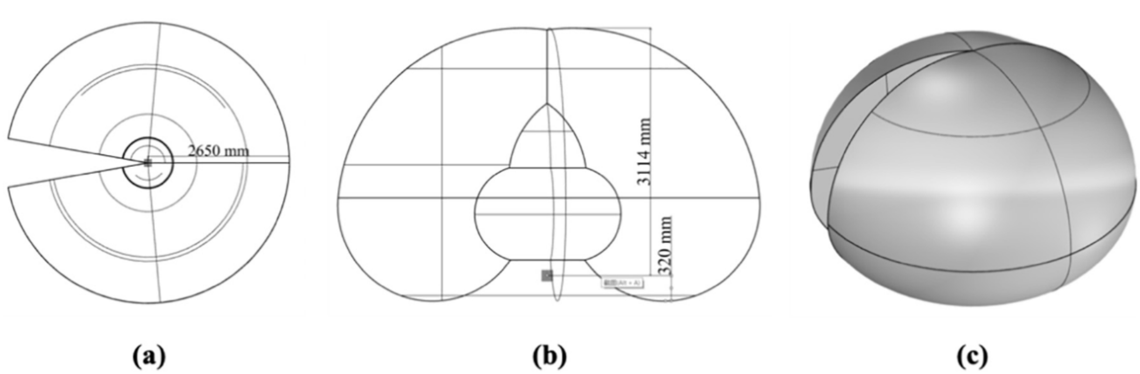

Fig. 4. Workspace of ABB IRB 6700, (a) horizontal plane, (b) vertical plane, (c) 3D envelope surface.

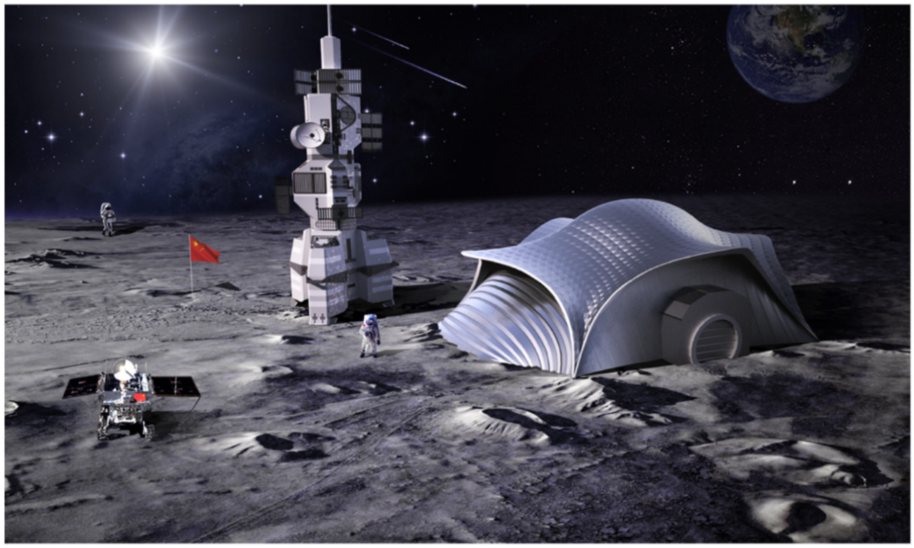

Fig. 5. Conceptual design of the Xuanwu lunar habitation.

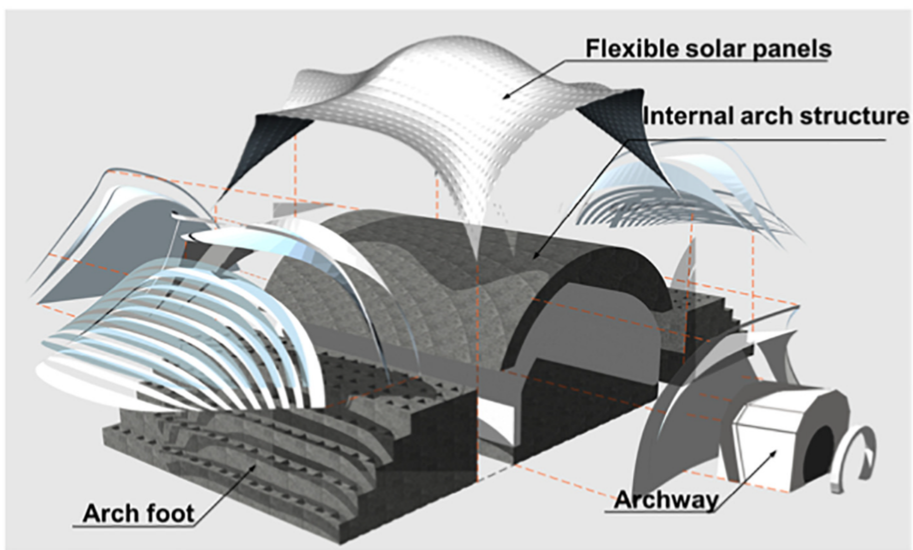

Fig. 6. Architectural breakdown map of the Xuanwu lunar habitation.

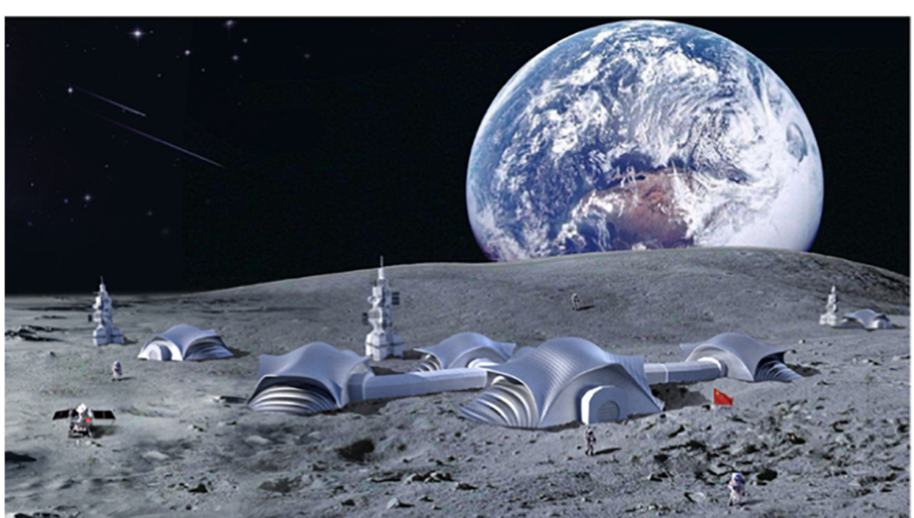

Fig. 7. Cluster schematic of the Xuanwu lunar habitation.

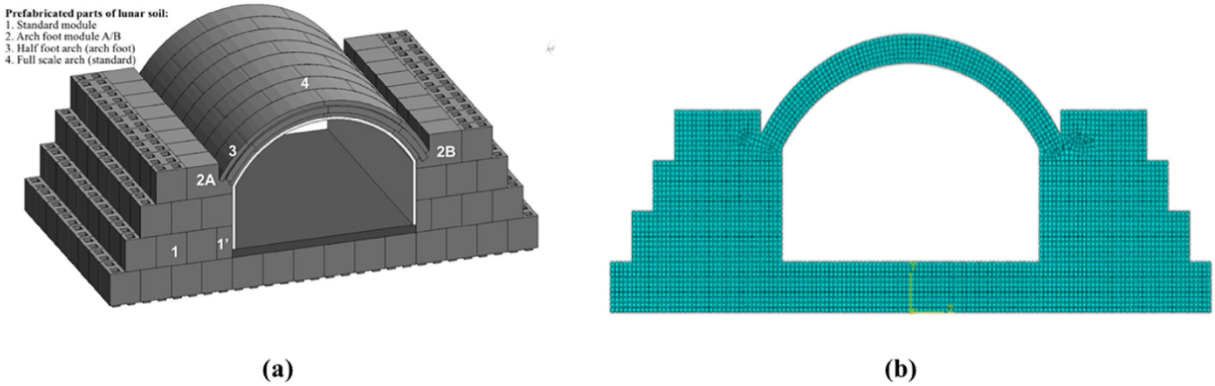

Fig. 8. (a) Structural design of the Xuanwu lunar habitation, (b) 2D finite element model of the proposed lunar structure.

bilinear plain strain quadrilateral) is used to simulate the cross section of the structure. A total of 3678 meshes are generated. The lunar regolith block is closed to concrete on the Earth; accordingly, several basic properties are assumed as follows: elastic modulus: 3.0×104 MPa, Poisson's ratio: 0.3, density: $2500\,\mathrm{kg/m^3}$. The considered static loads include the pressure that acts on the structure caused by the compacted lunar regolith layer, self-weight of the structure, and internal air pressure maintained when the habitation is in operation.

The loading conditions in the model are depicted in Fig. 9, and the model computation shows the following results: 1) principal tensile stress contours and 2) principal compressive stress contours. The results of the model computation, as demonstrated in Figs. 10 and 11, indicate that, in the construction stage, the maximum principal tensile stress is approximately 0.02 MPa, and the maximum principal compressive stress is 0.11 MPa; in the operation stage, the maximum principal tensile stress is approximately 0.66 MPa, and the maximum principal compressive stress is 0.11 MPa. Considering that the proposed lunar habitation is a prefabricated structure, the principal tensile stress governs the structural safety. In this case, the maximum principal tensile stress in the construction stage is only 0.02 MPa. Thus, the structure is relatively safe. However, the structural maximum principal tensile stress in the operation stage reaches 0.66 MPa, which is located at the connection part between the arch roof segment and the arch foot. Prefabricated structures cannot bear the tensile force as large as this level. We suggest that the internal air pressure must be undertaken by an internal membrane. Despite this suggestion, we recommend adding a certain special structural design to improve the tensile strength of the connection. A compacted lunar regolith layer with a thickness of 2.0 m is placed on top to shield the entire structure against the hostile lunar environment.

The proposed lunar habitation structure is relatively safe on compressive strength, but the tensile strength must be enhanced, especially the parts of the connection point of each module and the foundation fabricated by cubic blocks. Proper design requires an adequate comprehension of the stress distribution in the cubic block joggle joint connection point and its failure strength. The joint performance depends on many parameters, including geometrical and material parameters. The geometry of the joint and the intrinsic properties of the utilized materials determine the mechanical performance. Research has shown that the adhesion between the adhesive layer and the adherents and the cohesion of the adhesive layer after a cure can enhance the tensile strength of the lunar habitation.

5. In situ construction method of the Xuanwu Station lunar habitation

5.1. Material-molding process for a lunar brick

According to engineering application, the material-molding process for a lunar brick can be mainly divided into three categories, namely, a high-temperature sintering, wet mixing, and dry mixed autoclaving methods. Every category has different characteristics in the aspect of the material system, technology and equipment, preparation process, and application performance. To compare, explain, and increase comprehension further, we build a list to understand the differences between them and the aspect that must be suitable for the molding process, as listed in Table 2.

The high-temperature sintering method can improve the performance of lunar regolith components, while the mineral hardness distribution among layers is even. The tensile and yield strengths are high, but the plasticity index must be improved. However, the high energy demand is an extensive problem. For the wet mixing method, the workability, strength, and shrinkage of bricks are similar to the two other methods. The apparent density and strength of the hardened bricks obtained by the paste-wrapped stone-mixing process are probably higher than those built through the dry mixing process. The wet mixing process has higher compressive strength and lower early expansion rate than those of the dry mixing process. However, its fatal drawback is that this method requires considerable water. Under the restriction of energy consumption and water shortage on the Moon, the possibility of the material-molding method of the lunar habitation must be the dry mixed autoclaving technology [34–36]. Additional details are summarized in Table 2. This part addresses the possibility to apply

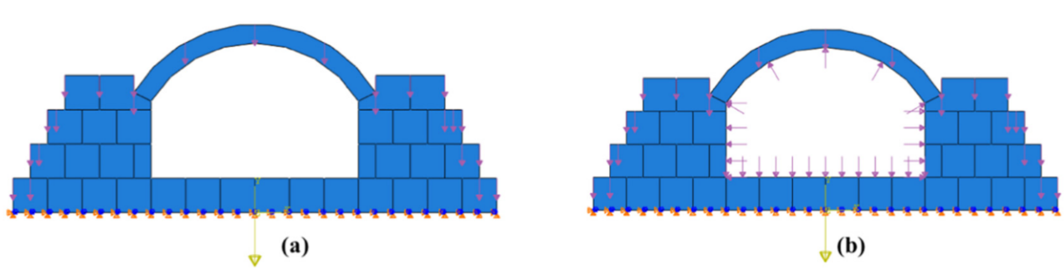

Fig. 9. Loading conditions for (a) construction stage, (b) operation stage.

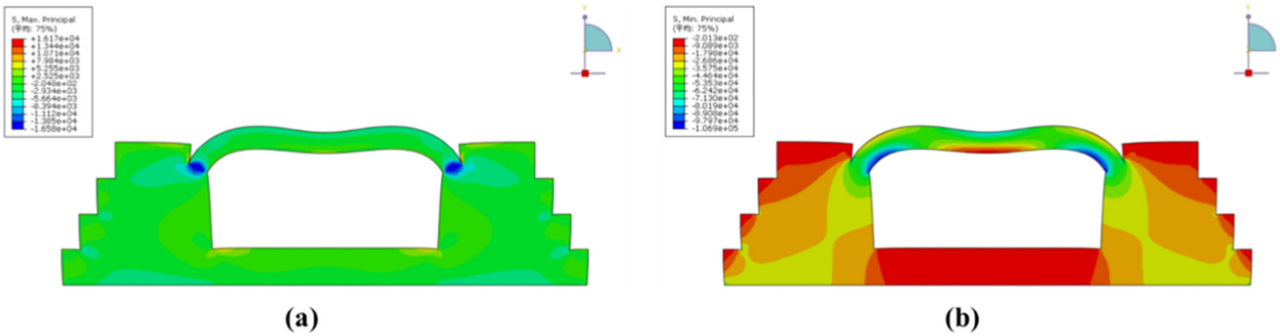

Fig. 10. (a) Principal tensile stress, (b) principal compressive stress in the construction stage.

the material preparation technology and the capability to explain their performances in terms of the utilization ratio of lunar regolith, technology maturity, energy demand, efficiency, and material strength. The results show that the dry mixed autoclaving method as the lunar regolith material-molding technology must be improved.

The incorporation of the preheating dry mixing concrete technology, a preparation process of lunar regolith bricks is established and extended to the lunar construction, as demonstrated in Fig. 12. On the basis of the preparation process, the technologies of the lunar regolith material collection and the lunar brick preparation are studied. Different steps are found to play an important role in the process. In comparison with material collection on the Earth, geological radar scanning, preparation, autoclaving preprocessing, and excavation increase the difficulty in the lunar environment; within a certain technology range, the basic process is similar [37]. The lunar soil will be collected and built into lunar bricks using dry mixed autoclaving equipment. With an increase in pressure, different shapes of standardized lunar bricks are produced.

5.2. *Autonomous construction robot: CSM*

Among various arched structure construction technologies, traditional Chinese stone arched bridge and metro shield segment construction are two most extensively used construction technologies. On the basis of the arched structure construction technology, the construction process is conducted systematically in the lunar environment, which is mainly related to the structural design of lunar habitation. Several steps of the lunar habitation construction process obtained directly from the metro shield segment construction methods are collected to fabricate the lunar bricks, recognize the modules, and grab and assemble the components, as exhibited in Fig. 13. A layer of lunar soil related to the thermal insulation and radiation protection is then implemented on the major structure. The pasting insulation material combined with the lunar bricks is supposed to increase the tensile and shear capacity of the structure. Finally, the inflatable skin and indoor layout are considered to protect astronauts' normal life.

We propose a control system called CSM for lunar habitation construction. The CSM can produce various prefabricated lunar habitation modules and other components using lunar soil materials extracted from the local environment. This study discusses the CSM in five parts, namely, supporting platform and moving device, lunar regolith molding device, compound robotic arm with multifunctional end-effectors, communication and navigation system, and intelligent sensing device and others. We will build the theory, method, and technology of the unmanned lunar habitation in the entire process of sensor–-actuator–controller, including the moving–power and material molding of the special structures, materials, and performance [38–41]. The synthesis of the control system of the CSM robot is presented in Fig. 14.

5.2.1. *Supporting platform and moving device*

The lunar surface is rugged, and the terrain is complex. To realize high-speed movement on the entire terrain, we propose a six-foot end-wheel mobility scheme as our extraterrestrial construction robot's moving method. The capability to move freely is required for exploring and collecting lunar soil resources and for altering construction location during construction. The mobile solution can be switched freely in two sport modes of six-legged walking and wheel driving using the stereo vision access, 3D points, atomic energy cell, and the electrode technology with a single-phase rectangular high voltage. The energy and sensing platform supply the energy through atomic energy cell when no sunlight is available (Fig. 15).

5.2.2. *Lunar regolith molding device*

The lunar surface construction robot with the material preparation equipment is required to satisfy the requirements of construction technology. In accordance with different functions, lunar regolith molding equipment can be divided into lunar soil acquisition and lunar block preparation. Comparing the four aspects of the raw material system, technical equipment, preparation process, and application performance, we select the high-temperature sintering method to achieve our goal. The lunar regolith molding platform gathers the native resources and fabricates the construction modules using a forward shovel excavator.

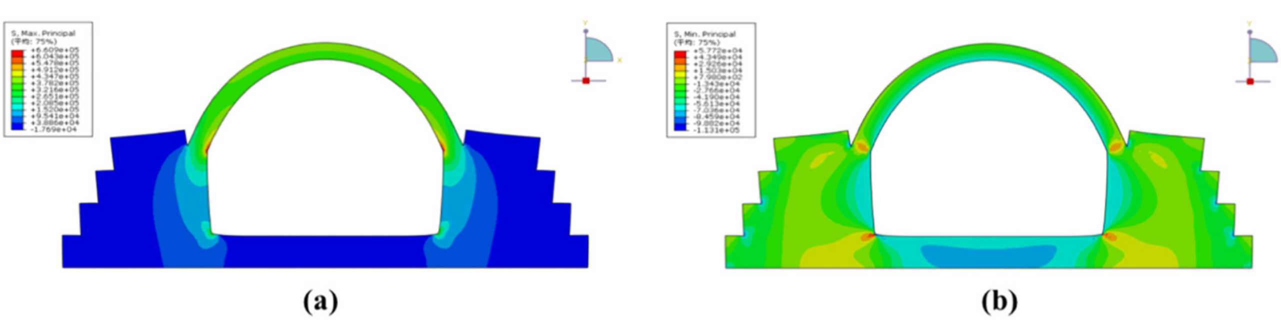

Fig. 11. (a) Principal tensile stress, (b) principal compressive stress in the operation stage.

Table 2
Contrast of the material-molding technology.

Type	Evaluating indicator	High-temperature sintering method	Wet mixing method	Dry mixed autoclaving method
Material system	Raw material complexity	★★	★★★	★★
	Utilization ratio of lunar regolith	100%	70%–80%	70%–80%
Technology and equipment	Equipment complexity	★★	★★	★★
	Technology maturity	★	★★	★★
Preparation process	Energy demand	★★★	★★	★★
	Temperature	900 °C–1000 °C	0 °C–100 °C	150 °C–200 °C
	Efficiency	★★★	★(time-consuming)	★★★
Application performance	Material strength	★★	★★	★★★

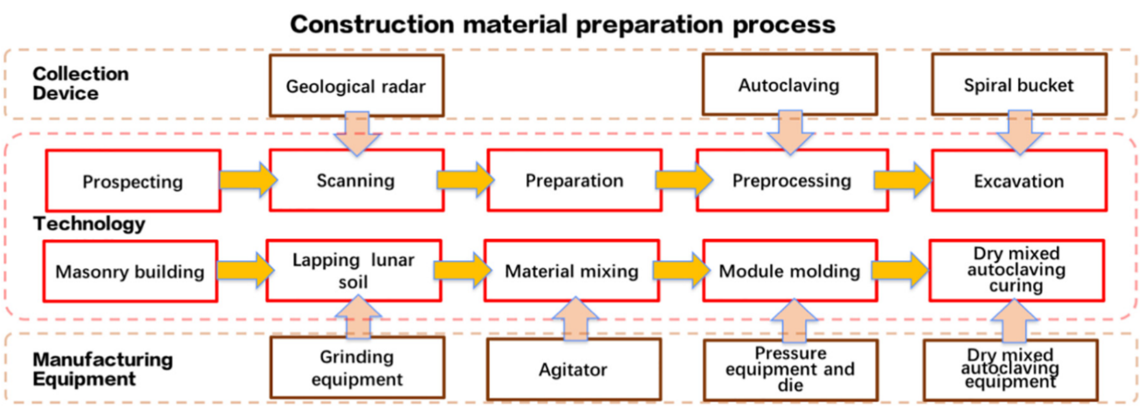

Fig. 12. Material preparation process of lunar bricks.

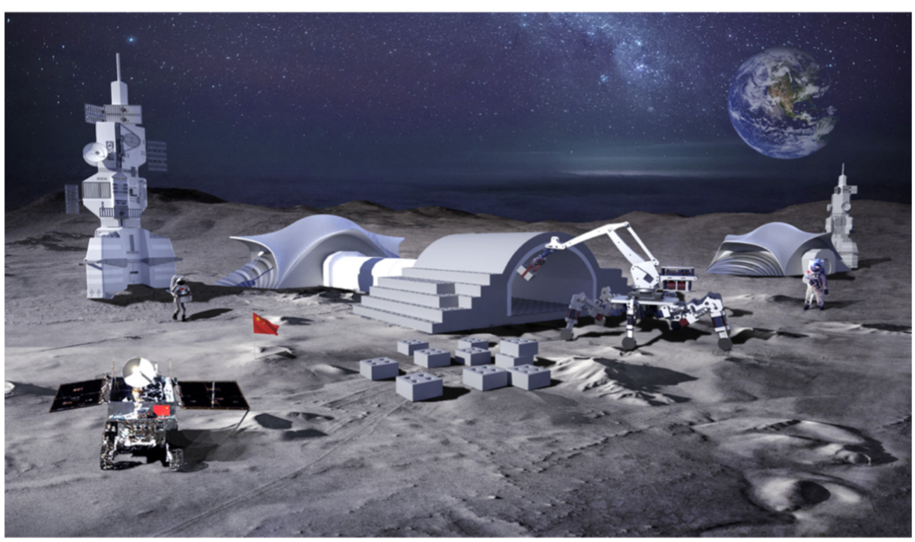

Fig. 13. Schematic of the Xuanwu lunar habitation construction process.

5.2.3. *Compound robotic arm with multifunctional end-effectors*

In terms of the construction technology of the habitation, we draw lessons from the traditional Chinese stone arched bridge construction and modern subway shield segment assembly construction methods. After completing the preparation of the lunar regolith module, the CSM arrives at the construction area, and the Xuanwu Station is ready to be built. The lunar regolith module is lifted by a mechanical arm equipped with a gripper, and the module is accurately installed in the designated position using computer vision guided by an autonomous construction system and a six-limbed wheel-on-limb mobility platform. The construction and mobility platform moves to the location of the construction materials. The construction planning site assumes that the native regolith has already been gathered and processed into construction materials.

5.2.4. *Communication and navigation system*

In accordance with the requirement of the CSM lunar habitation construction mission, the idea of a lunar relay communication satellite is referred to the relay communication satellite “Queqiao” for Chang'e 4 lunar farside exploration mission [42]. The main challenges are presented as follows: The frequency bands of relay communication are close to one another given the relay communication that is compatible with the state of the lander and the patrol. Simultaneously, the signal level received by a satellite is weak, and the radio frequency transmission power is relatively large considering the long distance of communication. The problem of electromagnetic compatibility that the communication links work at multiple frequencies and bit rates, in which the lowest bit rate is only 0.7 kbits/s, and the signal level received by the relay back-link is approximately 140 dBm must be solved.

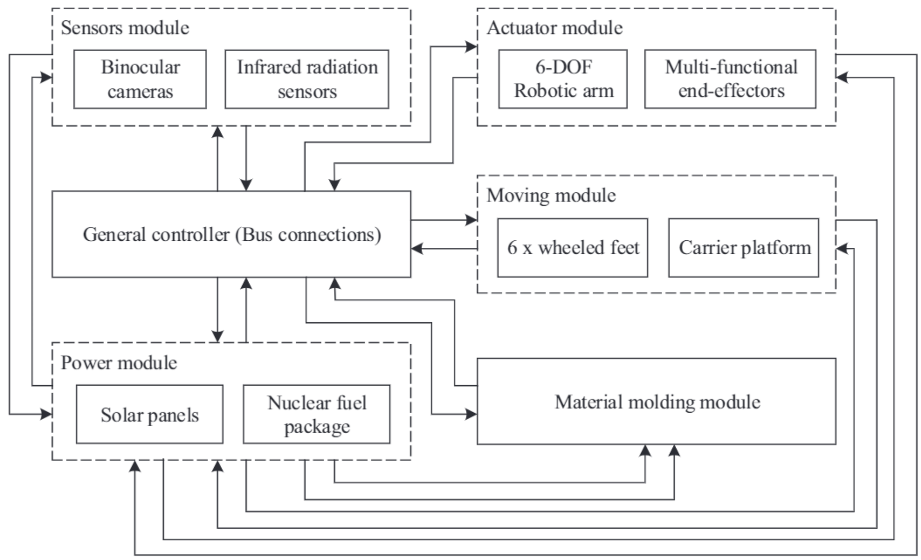

Fig. 14. Synthesis of the control system of the CSM robot.

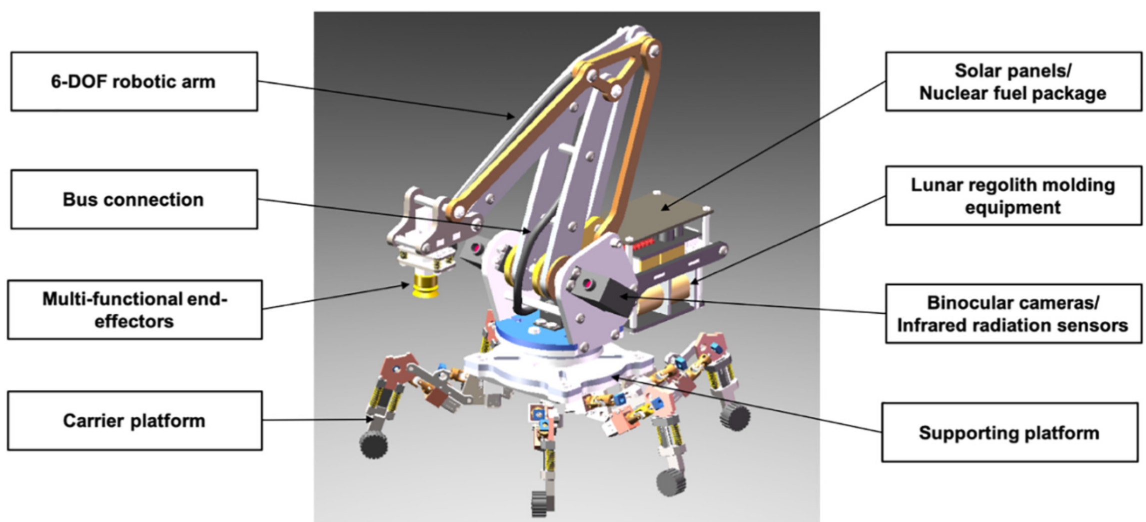

Fig. 15. Conceptual design of the CSM robot.

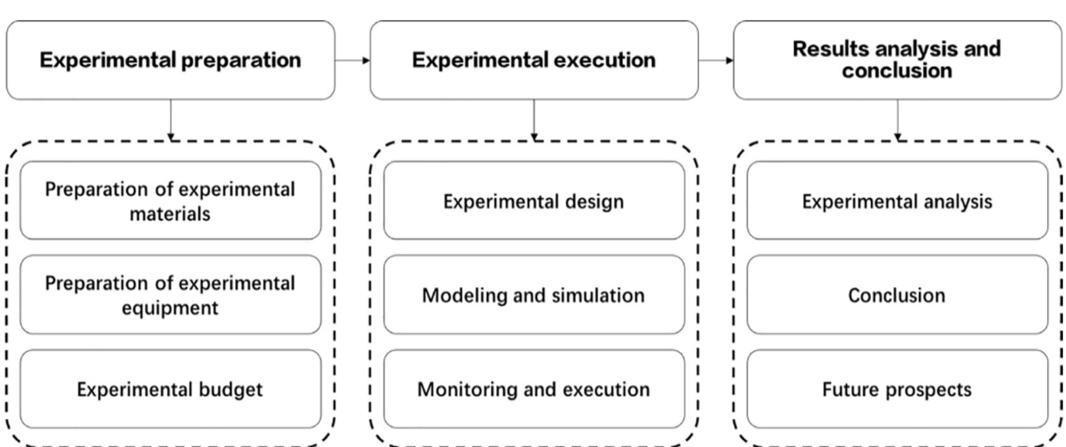

Fig. 16. Process design of the experimental method.

The size of the relay communication antenna directly determines the performance of the relay communication link. A large aperture and lightweight high-gain communication antenna must be selected to ensure the performance of the relay communication link. For example, the available beam range of an antenna is narrow and must be controlled in the range of 0.2°.

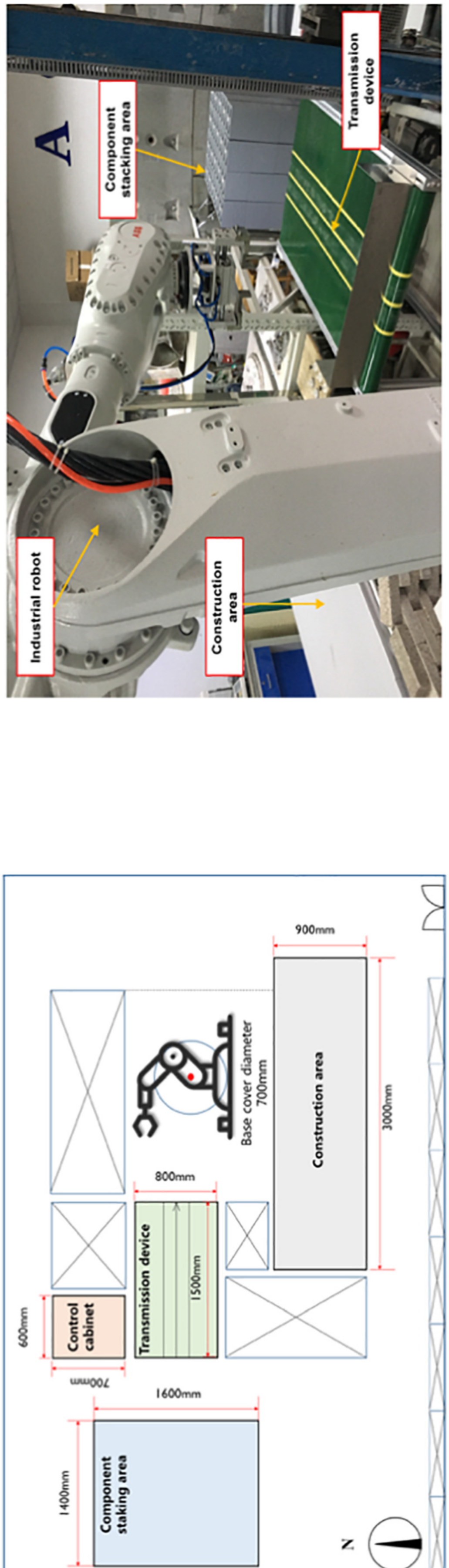

Fig. 17. Execution setup of the CSM.

5.2.5. Intelligent sensing device and others

The intelligent sensing device is equipped with a camera (machine vision) system, which consists of binocular cameras and infrared radiation sensors. In addition to high-precision control performance, energy efficiency is another vital characteristic in field-robotic hydraulic systems because energy supply must be carried in limited space and must be sustainable. We use a combination of two methods, that is, solar panels and nuclear fuel package, to provide an uninterrupted energy supply.

6. Experimental testing of the CSM on the Earth

6.1. Experiment design and preparation

This section illustrates the proposed methodologies for constructing the lunar habitation, including the experimental preparation, execution, and process. Considering that having the same extreme conditions on the Earth as on the Moon is difficult, we ignore these factors and focus on designing the experiment and construction process.

The entire experiment design and process include three aspects and are annotated below, as presented in Fig. 16. The materials and equipment must be prepared and the budget must be worked out to guarantee the smooth running of the experiment. Therefore, the experimental experience that was applied in the previous study is used in the present study as a reference. The experimental materials must be prepurchased in accordance with the plan, and the experimental equipment is operated and tested to avoid potential danger. The proposed ideas in the laboratory and the construction process are simulated in the building information modeling (BIM) software Revit. The analysis and conclusion of the results mainly consider the advantages and disadvantages of the experiment and future work.

On the basis of the structural design in Section 4 of this paper, the experimental scene in the laboratory, including the component staking area, control cabinet, transmission device, and construction area is laid out, as illustrated in Fig. 17. In the staking area, each component has a code, which follows the construction order that we have optimized in the BIM (Fig. 18a), and the transmission device (Fig. 18b) delivers the component to the industrial robot (Fig. 18c), which is controlled by the control cabinet (Fig. 18d) to catch the component with the functional fixture (Fig. 18e) to the construction area (Fig. 18f). All the experimental components are made of wood materials 5 times smaller than that we designed; these components are 2.8 m long, 0.8 m wide, and 1.1 m high. We build only half of the lunar habitation in the width direction given the site limitation.

The related parameters of several machines of the execution systems are listed as follows:

- The industrial robot and control cabinet are ABB IRB 6700–235, with a movement distance of the arm of 2.65 m, 235 kg load, and 0.05 mm repeat positioning accuracy.
- The transmission device is 0.8 m high, 1.5 m long, and 0.8 m wide, with over 8 kg weight negative, 1 m/min minimum speed, and 5 m/min maximum speed.
- The functional fixture is driven by an MHL2-40D cylinder with the same size of the component.

6.2. Construction simulation and automated execution

The construction process of the "pick and place" task is simulated in Navisworks for the three types of construction plans, as depicted in Fig. 19. When the BIM of the lunar bricks and the control coordinate system of the CSM are completed, the building model will be matched with the robot base coordinate system. The calibration process of the CSM is completed by setting the positive direction of the coordinate system to be aligned with the positive direction of the robot motion. The world coordinate system in the BIM software is then set as the robot

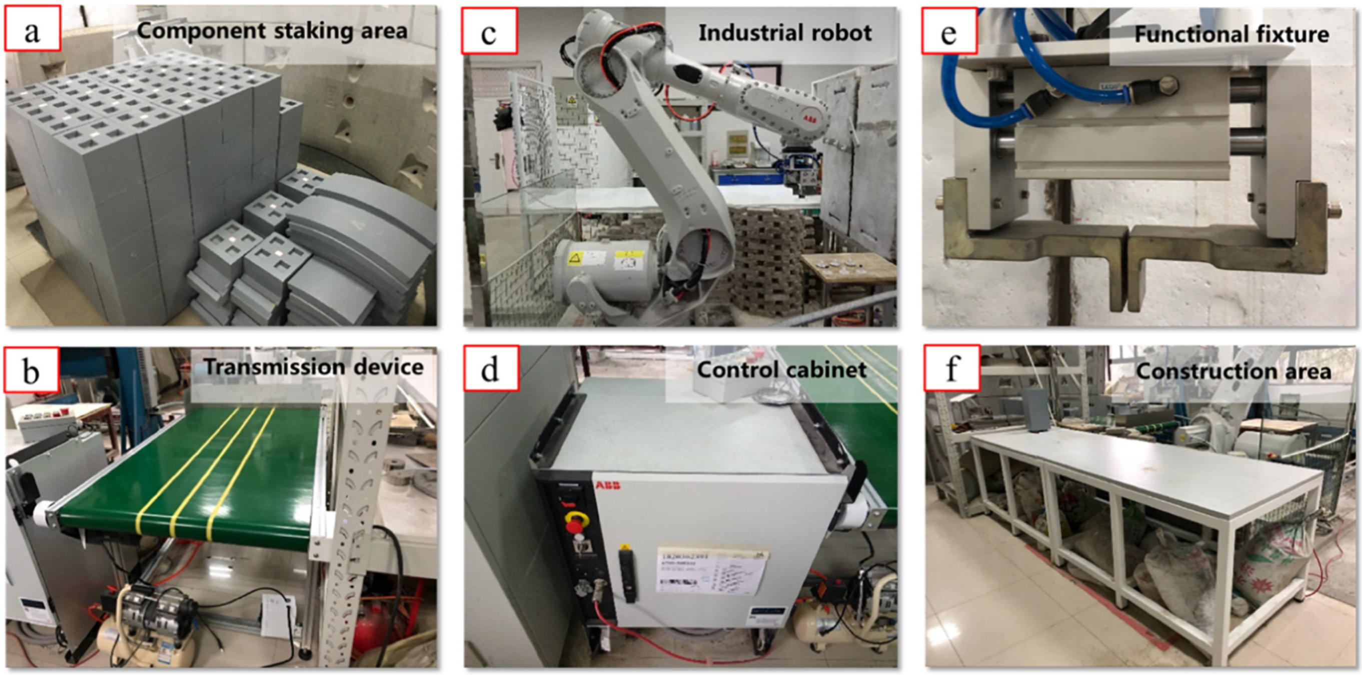

Fig. 18. Distribution composition of the CSM.

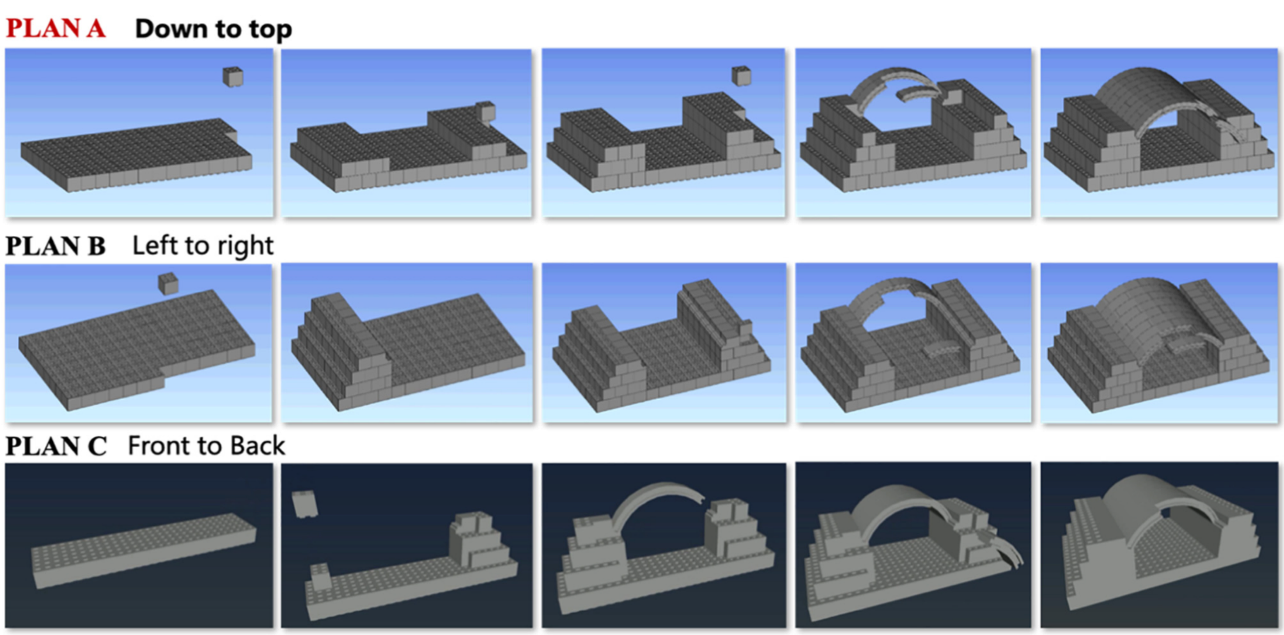

Fig. 19. Construction simulation of the lunar habitation.

basic coordinate system. An appropriate solution and the 3D coordinates of the placement points can be selected and output through the capability of the parametric calculation of the BIM platform. Simultaneously, these points are arranged in accordance with the construction order. Finally, a set of placement point coordinate files that are extractable will be generated in the BIM. For the general robot operating system, this file can be saved in "Excel" format for facilitating the robotic control program to be used at any time.

Experiments are conducted under the laboratory conditions. The autonomous robotic platform is mainly composed of an industrial robot, a transmission device, and a construction workbench. The motion path and speed of each operation of the robot are all controlled individually through control procedures to make the pose and the grabbing speed of the construction adjustable. The coordinates of these moving points we have calculated previously will be compared with those we acquire from the process simulation of the robotic lunar habitation construction. The data are obtained when we use the teaching apparatus to control the process accuracy. All operations are based on the ABB programming language. Accuracy control is important during the construction process, and the accuracy can even affect the quality of the lunar habitation. Therefore, the grasping and placing process can be attempted from different directions to test that the angle to be grasped is the most stable. The experimental process is conducted to simulate the construction process of the Xuanwu Station, as demonstrated in Fig. 20.

Fig. 20. Construction process of the lunar habitation.

Table 3
Cosine similarity analysis of coordinates.

Model	1	2	3	4	5	6	7	8
Cosine similarity	0.9992	0.9996	0.9996	0.9993	0.9992	0.9997	0.9991	0.9999
Mean cosine similarity	0.99945							

6.3. Experimental result analysis

Eight points are selected, and every point is measured from the actual coordinates of the robot operation. The same obtained dataset is used sequentially in the calculation. All the calculation results are listed in Table 3. In the presented experiments, the accuracy is the last two decimal points. In this task, cosine similarity analysis is implemented to estimate the similarity of two datasets, calculated by Eq. (3). The results are presented through the average cosine similarity. This value is close to 1, thus showing that the two datasets are highly correlated and reflecting that the recognition accuracy is high.

$$Similarity = \cos(\theta) = \frac{A \cdot B}{\|A\| \, \|B\|} = \frac{\sum_{i=1}^{n} A_i \times B_i}{\sqrt{\sum_{i=1}^{n} (A_i)^2 \times \sum_{i=1}^{n} (B_i)^2}} \tag{3}$$

7. Conclusions

This study presents an autonomous robotic construction method for a lunar habitation. The architectural design of a lunar habitation, namely, Xuanwu Station, was completed. A 2D numerical model of the recommended structural design was established in ABAQUS to investigate the structural behavior under extreme loading in the lunar environment. The material preparation and construction technology in the lunar construction were studied. An experiment was conducted to test the feasibility of the construction method. The following conclusions could be drawn from this study.

The Xuanwu Station, combined with Chinese traditional culture, was confirmed to be an efficient means of bringing the innovation and inspiration to the lunar habitation design. The use of parameterized and modular design techniques allowed for a comprehensive and feasible method for the Xuanwu Station construction. During the analysis of the finite element model, the arched structure was subjected to extreme loading in the lunar environment. The structure was safe in terms of compressive strength, but the tensile strength should be enhanced at the connection point of each module and the foundation fabricated by cubic blocks. The dry mixed autoclaving method could produce the lunar regolith bricks, including the lunar regolith material collection and lunar brick preparation. This method exhibited the advantages of energy saving, high efficiency, and feasibility. The proposed autonomous robotic construction method can be implemented in extreme environments on the Earth. The pasting insulation material was supposed to increase the tensile and shear capacity of the structure. The inflatable skin and indoor layout were considered to protect astronauts' normal life. During the conduct of this study, several limitations identified were due to the lunar extreme environment.

The identified limitations included, but were not limited to, the lunar ergonomics in architectural design, impact resistance of micrometeorites in structural design, lunar soil exploration and vacuum sintering in material preparation, autonomous artificial intelligence, and failure mechanisms in the lunar environment for mechanical design. Despite the challenges, the lunar habitation construction is feasible. While still in its prospection and exploratory stages, this study has the potential to improve the traditional automatic terrestrial construction methods and solve problems such as, high accident rates, low quality, and loss of skilled workers. For the construction equipment, the construction of artificial intelligence technology, advanced manufacturing technology, and other digital technology works provide technical support for equipment development in extreme environments and possible major scientific technical breakthroughs in the field of special unmanned equipment. Our study aims to propose a new idea and method, and considerable research on details that are overlooked in this study can be conducted. In the future, we can modify the mechanism of the interaction of the suspension with the lunar soil and the suitability for human living in extreme environmental conditions.

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