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Progress and trends in lunar habitat construction research based on bibliometric analysis

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Abstract

Various countries have proposed plans for lunar bases, and research on construction of lunar habitat has become increasingly important. A bibliometric analysis was conducted on 227 articles published in the Science Citation Index database using co-citation analysis, co-word analysis, and cluster analysis. Citespace was used to map the results. The research disciplines have shifted from chemistry, materials science, physics, and geography to mathematics and systems science, with a focus on eight directions and four themes. The research themes and frontiers have shifted from general structural concepts to feasible construction methods to more specific material technologies and unmanned construction techniques, exhibiting a trend from possibility to feasibility and from theory to practice. This article is expected to provide valuable references for scholars focusing on lunar habitat construction.

Keywords: lunar habitat, construction, bibliometric analysis, progress and trends.

1. Introduction

Exploring the vastness of the universe has been a dream of humankind since ancient times, and it may be an inevitable choice for them to deal with the increasing depletion of Earth's resources [1]. Establishing a lunar base is critical in extraterrestrial exploration [2]. A moon base can provide a transit hub for extraterrestrial exploration [3] and a research site for studying the complex space environment. Besides, lunar base construction can advance the development and utilization of lunar resources [4]. Various countries and organisations have proposed lunar exploration plans in recent years, such as the United States[5], the European Union [6], China [7], Russian [8], Japan [9] and India[10]. As the lunar exploration program continues to expand, the construction of lunar habitats has become a hot research topic. Lim et al. reviewed established extraterrestrial construction projects and discussed four types of challenges [1]. Naser and Chehab analyzed the impact of the harsh space environment on building structure and proposed the concept of space-elastic structures [11]. Ulubeyli developed a 3D printing process based on the salient issues of lunar base construction [4]. Cesaretti et al. explored the possibility of using in-situ resources for lunar habitat construction and fabricated components for a lunar outpost using D-shape printing technology and simulated regolith [12]. Meurisse et al. demonstrated the feasibility of solar sintering by 3D printing a lunar soil brick [13]. Despite the rapid development of research on lunar habitat construction in the past few decades, few studies have used bibliometric methods to visualize key areas and emerging trends making it difficult to identify research directions worth following. This study conducts a bibliometric analysis of lunar habitat construction and uses Citespace to visualize the results. The findings are used to outline the research themes and analyze the active research hotspots and development trends.

2. Research methodology and data

2.1. Research methodology

Bibliometrics is a type of information science. Bibliometric analysis of the literature reveals the knowledge structure and emerging trends in a research field [14]. Co-citation analysis can identify the most influential disciplines and domains in the research field [15]. Co-word analysis evaluates the affinity between keywords mapping the correlation between text information [16]. Cluster analysis evaluates the proximity between keywords and classifies closely related keywords into one category [17]. We use cluster analysis to categorize the results of co-word analysis into different knowledge fields which can inform future research.

2.2. Data collection

The Web of Science (WOS) core collection was chosen to obtain the publications to ensure the comprehensiveness and credibility of the data. Articles were searched using the search terms ‘lunar habitat’, ‘construction’ and their synonyms (Table 1). A total of 2879 documents were compiled. From this we excluded publications not related to the construction of lunar habitats and obtained 227 documents for bibliometric analysis. Citespace is a tool to analyze trends and patterns in scientific studies and to assess the boundaries of disciplinary advancement [18]. This study used Citespace to conduct bibliometric analysis. The study period was 1991-2022, with an interval of 1 year, the Top N was 50, and the Top N% was 10% to investigate the centrality and burst of keywords.

Table 1: List of synonyms of lunar habitat and construction to search the WOS

subject heading	synonym
lunar habitat	lunar architecture, lunar base, lunar habitat, lunar outpost, lunar colony, lunar station, lunar village
construction	construction, structure, fabrication, manufacture, building, erection

3. Result

3.1. Overview of research

As shown in Figure 1, the number of publications on lunar habitat construction (1991-2022) was compiled. An increasing trend occurred from 1991 to October 2022. Peaks in the number of publications were observed in 1991, 2000, 2007, and 2018. Large conferences were held in these years contributing to the development. An important reason for the surge in the research volume from 2020 to 2022, when the average number of publications was several times that of the earlier period, was that the United States, China, and Russia proposed long-term plans for the construction of human-resident lunar habitats in 2017 and 2021, respectively. In general, research in this field has just entered the proliferation stage.

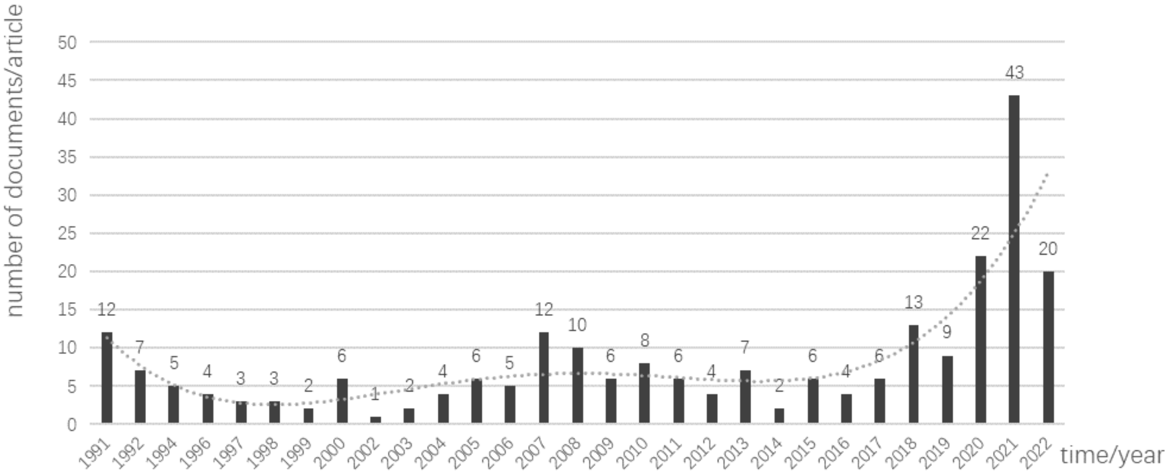


Figure 1: Number of publications on lunar habitat construction from 1991 to 2022

As shown in Figure 2, co-occurrence analysis of the disciplines about lunar habitat construction was conducted. Larger circles and fonts indicate a higher frequency of co-occurrence, thicker connecting lines indicate closer cooperation between the two, purple outer circles indicate high intermediary centrality (more cooperation with other disciplines), and red outer circles indicate high prominence (rapid development) [19]. Research on lunar habitat construction has a strong connection with aerospace engineering (81%) and civil engineering (27%), followed by astrophysics, earth science, and materials science (more than 10%). There are connections with construction technology, multidisciplinary engineering, atmospheric science, robotics, and geological engineering (more than 7%). The results indicate that the construction of lunar habitats is the result of interdisciplinary research.

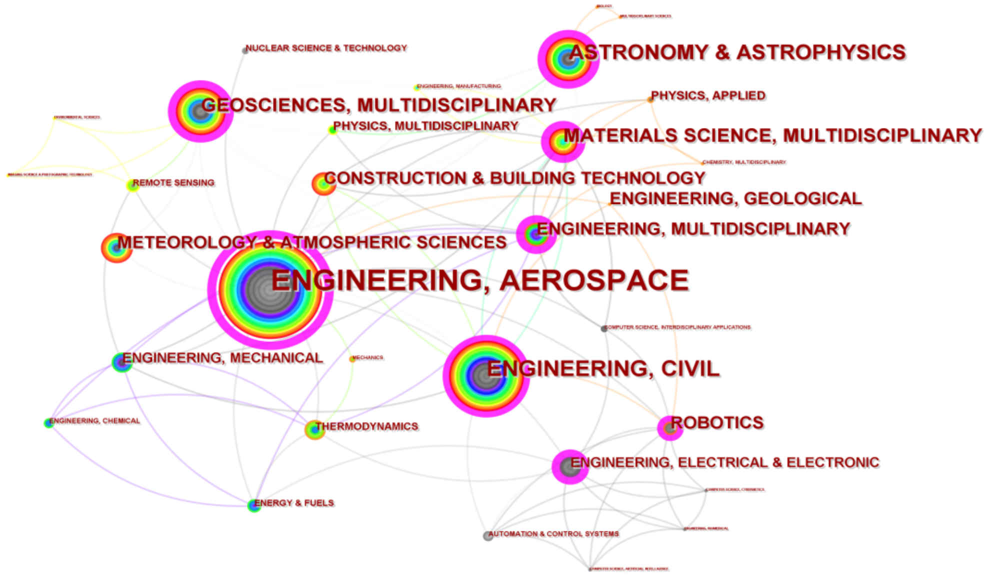


Figure 2: Disciplinary areas related to lunar habitat construction research, 1991-2022

As shown in Figure 3, the double graph overlay shows the citation tracks, intellectual flows, and spread of publications across the subject domains [20]. The citing literature on the left represents major domains in research of lunar habitat construction, and the cited literature on the right represents the topics cited in major domains. Thus, the former indicates the application and the latter the basis [21]. And the curves show the start, end, and linkages of the citations. The subject domains of citing journals include mathematics and systems science, whereas those of the cited journals are chemistry, materials science, physics, earth science, and geography. Thus it can be found that the center of the subject domain is increasingly shifting from chemistry, materials science, physics, earth science, and geography to mathematics and systems science.

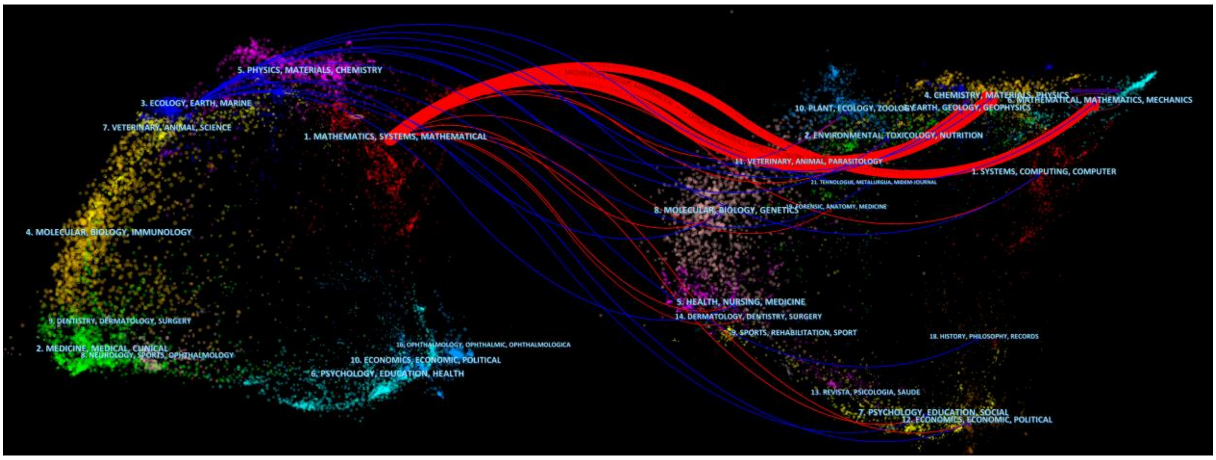


Figure 3: A double graph overlay showing the relationship between the citing literature and the cited literature

3.2. Research Frontiers

3.2.1. Keyword co-occurrence analysis

Dispersion and progression of research themes identify research hot spots and frontiers and their trends. Since keywords are indicative of themes and topics of publications, keyword co-occurrence analysis reveals the hot topics and evolutionary trends in study areas [22]. As shown in Figure 4, The results of the keyword co-occurrence analysis contains 317 nodes and 972 links. The size of the node indicates the co-occurrence frequency. The color of the nodes ranges from black and white to various colors and from purple to red, indicating the co-occurrence time from far to near. The color of the link represents the occurrence time of the keyword. Several nodes have purple rings, showing high centrality values. Citespace output 317 high-frequency keywords. Keywords with the same meaning were merged. For example, "lunar outpost", "lunar architecture", "lunar habitat ","lunar habitation " were merged into "lunar habitat". Next to the keyword "lunar habitat", the most frequent keyword is " regolith", followed by " construction", "exploration", "regolith simulant" "moon", and "design", indicating that these key words represent current research hot spots. "Lunar habitat" appears in most years, indicating that lunar habitat is an important research subject in lunar habitat construction. The frequency of "regolith" ranks second after "lunar habitat", suggesting that a large part of current research on lunar habitat is related to the study of regoliths as a building material. Additionally, the terms "exploration" and "design" of lunar structures and construction processes account for a large proportion of the keywords. The high-frequency keywords are highly concentrated, showing that the research hot spots are closely linked.

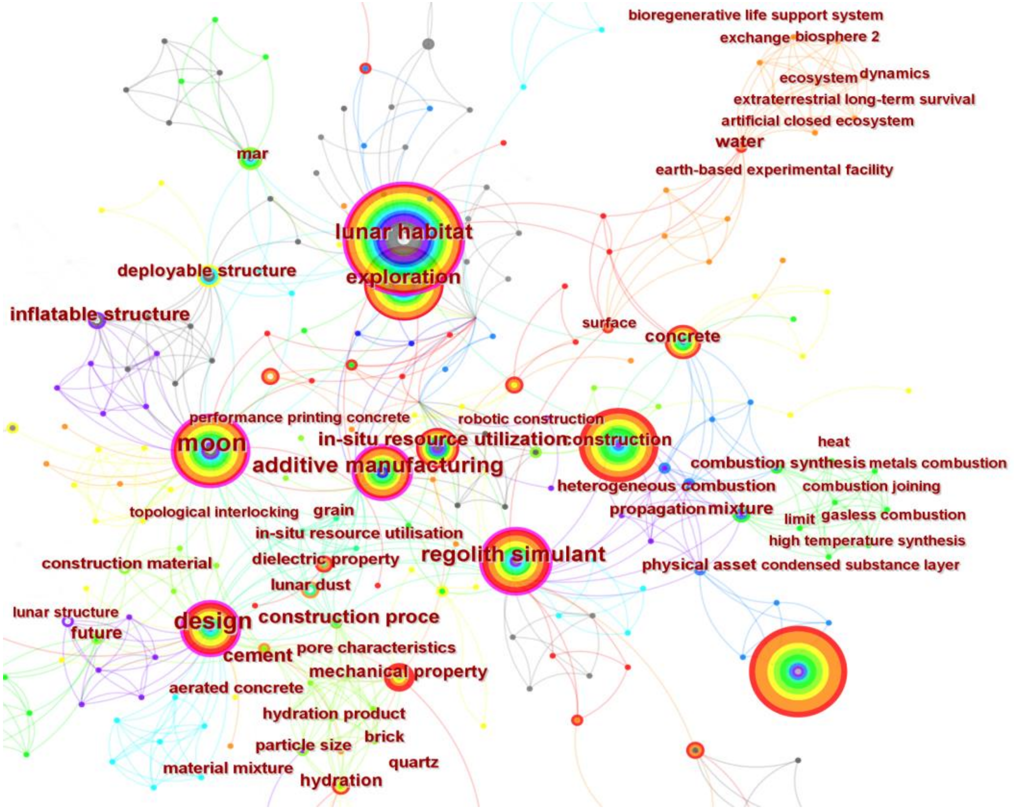
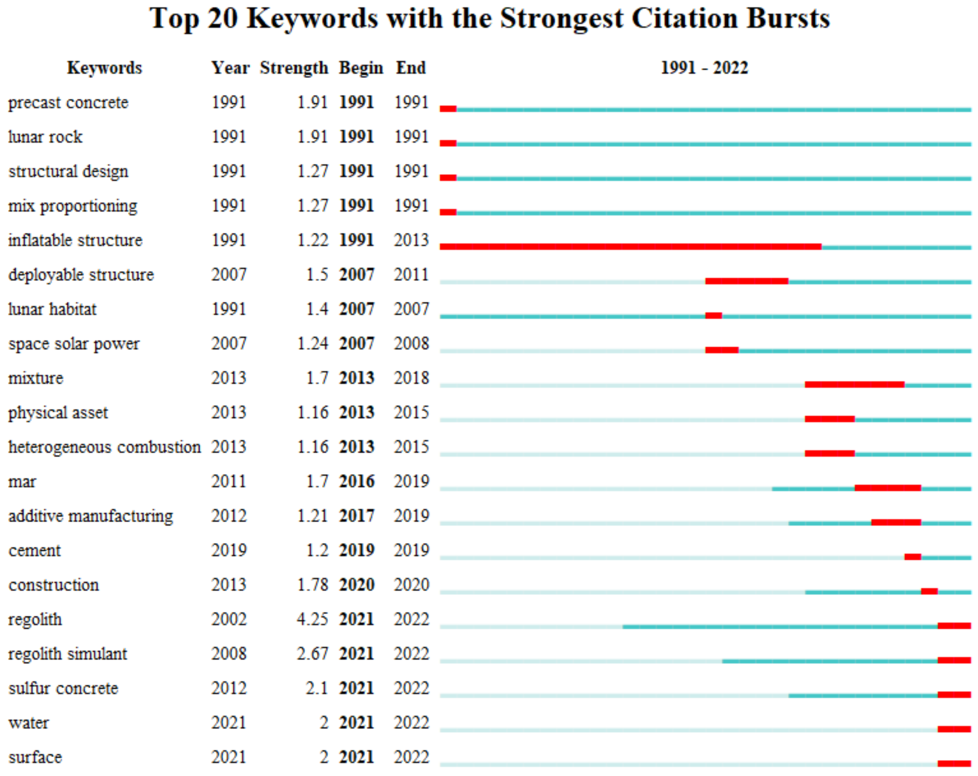


Figure 4: Keyword co-occurrence map of lunar habitat construction research

3.2.2. Keyword burst analysis

A keyword burst is a sudden increase in the use of keywords within a short-term period. It is analyzed to observe trends in keyword frequency in a specific period and identify impactful topics within a domain. It is evaluated using burst strength and persistence [21]. The burst detection algorithm yielded 20 burst terms, which were ranked by the keyword burst strength, as illustrated in Figure 5. The term 'Begin' indicates the first year of the burst period, 'End' indicates the last year of the burst period, red indicates the burst duration, and blue indicates the time piece of the unit. The burst intensities of "regolith" and "regolith simulant" have the two highest values, suggesting that the study of regoliths and regolith simulants will be critical in the future. This research has increased rapidly after the return of the Chang'e 5 sample in 2020 and has been popular in the past two years. The burst strengths of "sulfur concrete" and "water" are also high because research on anhydrous concrete has been of great interest in the past two years. "Inflatable structure" has the longest burst time (from 1991 to 2013), indicating a hot topic. Research on lunar habitat has exhibited different themes and research frontiers in each period, ranging from structural selection to construction methods to material technologies. In 1991, research began on the "structural form" of the lunar module, focusing on integral structural design and inflatable structures. After 2007, the keyword content began to shift to the influencing factors of the moon environment and feasible construction approaches. Through 2018, the research focus shifted to technology, such as materials and unmanned construction. The research focus during the 30 years changed from general to specific, from possibility to feasibility, and from theoretical concepts to experimental verification.



Top 20 Keywords with the Strongest Citation Bursts

Keywords	Year	Strength	Begin	End
precast concrete	1991	1.91	**1991**	1991
lunar rock	1991	1.91	**1991**	1991
structural design	1991	1.27	**1991**	1991
mix proportioning	1991	1.27	**1991**	1991
inflatable structure	1991	1.22	**1991**	2013
deployable structure	2007	1.5	**2007**	2011
lunar habitat	1991	1.4	**2007**	2007
space solar power	2007	1.24	**2007**	2008
mixture	2013	1.7	**2013**	2018
physical asset	2013	1.16	**2013**	2015
heterogeneous combustion	2013	1.16	**2013**	2015
mar	2011	1.7	**2016**	2019
additive manufacturing	2012	1.21	**2017**	2019
cement	2019	1.2	**2019**	2019
construction	2013	1.78	**2020**	2020
regolith	2002	4.25	**2021**	2022
regolith simulant	2008	2.67	**2021**	2022
sulfur concrete	2012	2.1	**2021**	2022
water	2021	2	**2021**	2022
surface	2021	2	**2021**	2022

Figure 5: Ranking of keyword bursts of lunar habitat construction research

3.2.3. Keyword cluster analysis

The cluster analysis of high-frequency keywords is shown in Figure 6, where the keywords are grouped into 8 clusters: "additive manufacturing (#0)" "inflatable & deployable structures (#1)" "in situ utilization (#2)" "combustion synthesis (#3)" "robot & construction (#4)" "structural optimization (#5)" "lunar concrete (#6)", and "life support system (#7)". The cluster size of additive manufacturing was the largest, indicationg that it is the hottest research direction. Inflatable & deployable structures and in situ utilization ranked second and third. The smaller clusters included structural optimization, lunar concrete, and a life support system, indicating the potential for development. Some overlap exists between the clusters, such as "additive manufacturing" and "in-situ resource utilization", suggesting links between them. The eight clusters of lunar habitat construction were classified into four levels based on their meanings: construction methods and strategies, construction principles, construction material processing technology, and basic conditions of construction. Specifically, the construction methods and strategies include additive manufacturing (#0), inflatable & deployable structures (#1), and structural optimization (#5). The construction principle includes in situ resource utilization (#2) and robot & construction (#4). The construction material processing technology includes combustion synthesis (#3) and lunar concrete (#6). The basic conditions of construction include the life support system (#7).

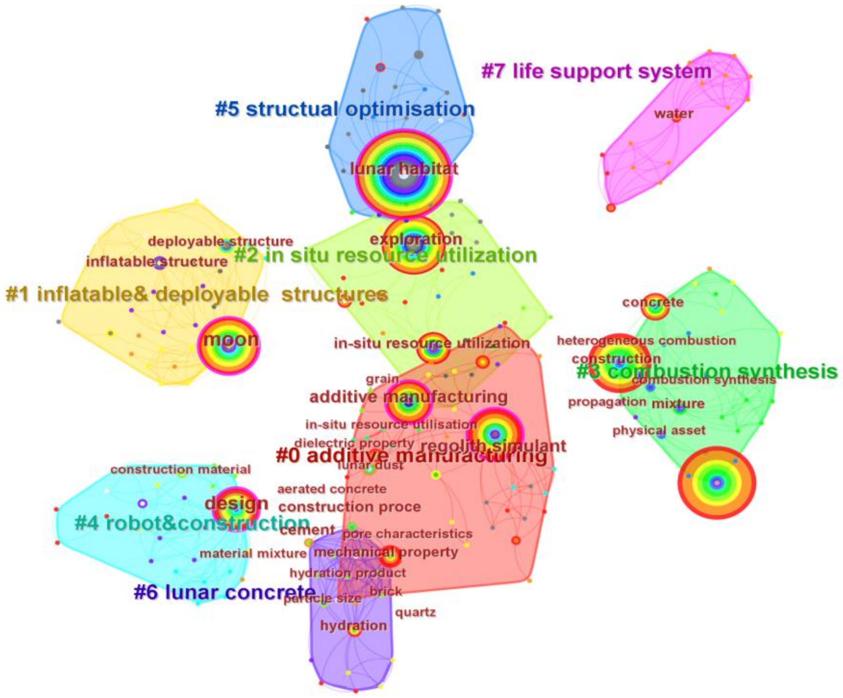


Figure 6: Cluster map of keywords of lunar habitat construction research

3.3. Research themes for lunar habitat construction

3.3.1. Construction methods and strategies

Additive manufacturing (#0): Additive manufacturing, also called 3D printing, refers to constructing 3D objects based on a digital 3D model by layering material. This is a crucial method for building lunar structures and infrastructure based on in situ resource utilization [1]. In this cluster, "regolith simulant", "additive manufacturing", and "lunar dust" were the most frequent keywords. Lunar soil and dust are potential materials for building lunar structures. Thus, analyzing their chemical composition, mechanical properties, and dielectric properties is critical for implementing additive manufacturing on the Moon. Since regolith is difficult to obtain, regolith simulants are typically used for additive manufacturing experiments. The NASA Marshall Space Flight Center (MSFC) has defined the standards for the development of simulated lunar materials. There are currently 30 types of regolith simulants, but none adequately simulate the chemical diversity and particle shape characteristics of an actual regolith [1]. Thus, more research on simulants is required. The technologies for additive manufacturing using regolith can be divided into two categories: regolith with and without additives. Technologies for regolith without additives include regolith sintering, such as laser sintering, solar sintering, microwave sintering, and fused deposition modeling. Technologies for regolith with additives include contour crafting, D-shape technologies, and concrete printing technologies. Microwave sintering has the most research potential [1], although the relationship between the dielectric properties of regolith and the sintering efficiency requires further investigation.

Inflatable & deployable structures (#1): Inflatable & deployable structures refer to prefabricated lunar structures that are unfolded on the moon. "Moon", "deployable structure", and "inflatable structure" were the most frequent keywords. The gravity level of the Moon is about 1/6 of that of the Earth. Therefore, structural components can be thinner and consist of lower-density materials, providing favorable conditions for using inflatable & deployable structures [11]. Inflatable & deployable structures have a high good bulk-to-quality ratio and high packaging efficiency, providing more space and lower transportation costs, while requiring fewer construction materials on site. The technology is also relatively mature [23]. They have structural elements consisting of soft materials, such as fabrics, foams, and elastic polymers that are folded. They are unfolded by pressurization and mechanical actuation once in place and maintain their stiffness by the pressurization of the structure or by various rigid mechanisms

[23]. In previous studies, deployable structures were folded and unfolded using bionic-inspired methods [24].

Structural optimization (#5): Due to the long distance between the Moon and Earth and the expensive transportation, structural optimization should focus on using regolith as the main construction material and solar energy as the energy source for construction to maximize in situ resource utilization. "Lunar habitat", "space solar energy", and "finite element analysis" were the most frequent keywords. Researchers have proposed a systematic scheme and specified that a 1-2 m thick layer of regolith was required to shield humans from radiation. The constraints of structural loading include gravity, lunar shock, and thermoelastic loads [12]. Solar energy is the dominant energy source for construction. It has higher efficiency than on Earth because the Moon has no atmosphere. Finite element analysis has been used to simulate the mechanical properties of inflatable structures [25] and large-span arch structures [26]. This method is effective and accurate in simulating the lunar habitat in the microgravity environment of the Moon. Further research on structural strategies should focus on comprehensive and suitable habitat solutions and an adequate energy supply in the built environment.

3.3.2. Construction principles

In situ resource utilization (#2): In situ resource utilization refers to the utilization of in situ resources to manufacture a product or generate a service to enable exploration by robots and humans [11]."Exploration" "in situ resource utilization" and "ash" were the most frequent keywords. The success of early lunar exploration missions enabled the assessment of in situ lunar resources and the start of in situ resource utilization [11]. In addition, it is necessary to establish lunar bases and reduce the fuel required for takeoff to optimize future space exploration [12]. Due to the very high cost of space transportation, scientists are aware of the need to use local resources and find effective processing approaches to manufacture building materials from elements and minerals extracted from local materials [11]. The use of in situ lunar materials includes high-temperature sinter-hardened construction materials and the production of sulfur concrete and geopolymers using the sulfur in lunar soil [27]. Due to the low strength of sintered products and the inability of sulfur cements to resist the high temperatures on the Moon, research has focused on geopolymers whose raw materials are abundant in the lunar regolith and whose binder body is the lunar regolith [28].

Robotic & construction (#4): Robot & construction refers to intelligent or semi-autonomous construction, including additive manufacturing. "Design" "construction material", and "lunar structure" were the most frequent keywords. In the extreme and dangerous lunar environment, it is impractical to use a large number of human workers for construction; therefore, early construction was performed mainly by robots [1]. Additive manufacturing has been extended to unmanned construction, such as contour crafting and 3D concrete printing systems using extrusion-based additive manufacturing technologies. However, the application and development of new construction technologies have been slow, and the research history is relatively short. Research in the robot & construction field should focus on the design of the printing system, the collection and delivery of materials, the reinforcement and radiation shielding of the infrastructure, the design of specific locations, and dust reduction measures, in addition to material manufacturing technology. Developing an automated, large printing system for lunar construction is a top research priority [1].

3.3.3. Construction material processing technologies

Combustion synthesis (#3): Combustion synthesis refers to heating porous material, such as regolith, to below the melting point to bind the particles together while reducing the pore volume to form a solid. "Regolith", "construction", and "concrete" were the keywords of this cluster. The regolith is the weathered layer of the lunar surface. It consists of grains less than 1 cm in size and has a good particle size distribution, making it an excellent building material in space. Processing requires only mechanical screening and no crushing, resulting in minimal damage to the lunar surface [1]. Combustion synthesis includes three sintering techniques using laser, solar, and microwave as energy sources [1]. Goulas et al. experimentally demonstrated the feasibility of laser and solar sintering of lunar soil. They discovered several disadvantages and eventually chose the more advantageous microwave sintering technique [1, 29]. In addition to regolith sintering, lunar concrete also appears frequently in related research.

Lunar concrete (#6): Lunar concrete preparation is critical for preparing materials for lunar base construction. Concrete was once considered the most suitable material for space structures because of its proven resistance to radiation and high temperatures in surface applications. "Mechanical properties", " cement", and "hydration" were the high-frequency keywords in this cluster. The mechanical properties, durability, and preparation difficulty are critical indicators for evaluating lunar concrete. Hu et al. evaluated and compared aluminate concrete, sulfur concrete, magnesium-silica concrete, polymer concrete, and geopolymer concrete [30]. In addition, cement is necessary for preparing lunar concrete. They also evaluated calcium aluminate cement, sulfur, magnesium oxide, organic polymers, and geopolymers, which are more advanced cement types [30]. Hydration to cure concrete remains a major limitation in the lunar environment. Several researchers investigated non-hydraulic concrete and alternative methods, such as the Dry-Mix/Steam-Injection (DMSI) method, hot melt method, mechanical extrusion, and high-pressure steam [30]. In general, regolith sintering and lunar concrete preparation are the most important processing technologies for lunar construction materials. These methods have shortcomings and limitations, but research is ongoing.

3.3.4. Basic construction conditions

Life support system (#7): The life support system provides a living environment for people in the extreme environment of the lunar surface. It is an essential component of lunar construction. "Water", "surface", and "extreme environment" were the most frequent keywords of this cluster. Water influences the site selection of lunar structures[31] and the construction method [30]. It is a crucial substance in the biochemical circulation system and is required for many lunar concrete preparation processes. Mineral resources and the topography of the lunar surface must be considered in lunar construction [32]. The extreme environment results in many constraints of lunar construction, including the near-moon space environment (high vacuum, strong radiation, micrometeoroid impacts) and the lunar surface environment (large temperature differences, long days and nights, and lunar dust particles), affecting the safety of human life and building operations.

4. Conclusion

This study systematically reviewed the literature on lunar habitat construction from 1991 to 2022 using bibliometric analysis and knowledge mapping. We analyzed 227 publications and performed co-citation analysis, co-word analysis, and cluster analysis. The results were visualized and interpreted. The following conclusions were drawn.

(1) The volume of research on lunar habitat construction showed an increasing trend in the past 32 years, with a rapid increase since 2020, suggesting that the research has entered the proliferation phase. The prospect of lunar habitat construction research is very broad.

(2) Aerospace engineering and civil engineering are the two most common disciplines related to studies of lunar habitat construction. Interdisciplinary studies are common, including astrophysics, earth science, materials science, robotics, and geological engineering. The center of subject domain in lunar habitat construction has shifted from chemistry, materials science, physics and Earth science to mathematics and systems science.

(3) "Regolith", "construction", "exploration", "regolith simulant", "moon" and "design" are core keywords in the field. Much attention has been given to research on the use of regolith for the construction of lunar habitat.

(4) Research has developed different themes and frontiers over time, with researchers gradually moving from exploring the possibility of constructing lunar habitats to viable construction methods under the influence of the lunar environment, with a gradual focus on the areas of materials and unmanned construction techniques.

(5) The eight clusters including additive manufacturing, deployable & inflatable structures, structural optimization, in situ resource utilization, robot & construction, combustion synthesis, lunar concrete and life support systems represented the hotspots and frontiers. The additive manufacturing has received most academic attention and is of considerable research value.

Acknowledgements

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