Learning lessons from Earth and Space towards Sustainable Multi-planetary Design

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Abstract

Off-Earth structural design has been a subject of fascination and research for decades. Given that the vision of permanent lunar and Martian human presence is materialising, it is an opportune moment to reflect on the future applicability and challenges of off-Earth design. This article investigates contemporary thinking about off-Earth structural design – specifically focused on large-scale infrastructure such as habitats – and assesses it in terms of its sustainability. We suggest that the extra-terrestrial setting, which is characterised by resource, construction, and labour constraints, is to be analysed as an extreme case of the built environment on Earth. Subsequently, we propose that structural design methodologies originating on Earth can benefit both the off-Earth context, through their inherent material efficiency and use of local materials, and the on-Earth context, where unsustainable growth and material inefficiency dominate our built environment. As our planet rapidly heads towards a scarcity of construction materials and disruptive environmental change, what sustainability lessons can we learn from our past, and how can we apply these to extra-terrestrial construction? Finally, how can we use these lessons to futureproof our built environment?

Keywords

Off-Earth Design, Space Architecture, In-Situ Resource Utilisation (ISRU), Material Efficiency, Reusability, Sustainability, Form-Finding, Structural Design

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Context

As public and private international initiatives to construct a permanent presence on the lunar surface come closer to reality, so too do the challenges faced by construction here on Earth. Specifically, material scarcity, climate change, and loss of biodiversity are beginning to impact our well-being and society.

In this paper we give an overview of contemporary engineering and design approaches for extra-terrestrial habitations, comparing them with pre-industrial vernacular and contemporary terrestrial structural design approaches. By identifying the similarities, lessons learnt from one can be applied to the other; for instance, in terms of material efficiency, use of local materials, and construction approaches.

Current thinking would position off-world construction as a largely separate field to conventional construction practice, rather than as an extreme example of it. In drawing the two domains closer together, we aim to create more of a bi-directional relationship, where off-Earth construction acts as a catalyst for change here, and on-Earth structures as a precedent for lunar and Martian construction.

Off-Earth structures

In this paper, we will use a broad definition of off-Earth construction, including any enabling infrastructure, such as berms, landing pads, roads, and habitation. Assuming a phased approach with increasing complexity of habitations over time, we can distinguish five classes of off-Earth construction: Class I are single prefabricated pressurised modules, such as the Apollo lunar lander; Class II are multiple such modules connected together on the surface; and Class III combines multiple modules plus structures built from in-situ materials (Howe et al., 2013). Extending this, Class IV would be constructed solely from local materials, and in Class V the construction machines would themselves be fabricated in-situ (Wilkinson et al., 2016a). Our focus here is on Class III, using in-situ resources for construction of heavy-weight infrastructure, such as a regolith shield.

For protection from radiation over extended periods, the construction of a regolith shield is a logical alternative to transporting heavy shielding from Earth. Other in-situ resource utilisation (ISRU) radiation protection options exist, such as water or extracted metals, which may provide a thinner structure, yet regolith is abundant and easily collected, and therefore assumed to be a principal construction material at the outset. A shield built from surface regolith has many advantages: protection from cosmic radiation, solar flares, dust storms, micro-meteorites, and temperature variations, as well as increasing the durability of the habitat modules within (Mueller et al., 2016).

On-Earth structures

In contrast to its off-Earth counterpart, on-Earth construction has evolved over the course of human history, from caves to primitive forms of shelter – in ancient vernacular periods – to the contemporary technological advances in computational methods for form-finding, topological optimisation, and automation in fabrication and construction.

Over the years, humanity has collectively built a vocabulary of infrastructures using diverse techniques and materials to withstand the test of time in different climatic environments (Oliver, 1997). From monolithic to component-based structures, natural and synthetic materials, we have a long history of on-site physical experimentation to learn from. In addition, with the advent of and advances in computation, we can now simulate structures in-silico with sophisticated methods. These enable us to input the physical properties of materials, forces, and environmental conditions to produce reliable and ever more precise predictions of structural behaviour and form. Furthermore, these can be combined with fabrication and construction automation techniques which have become feasible through the development of industrial, or bespoke, robotic and machinery systems. As a result, we have never been in a better position to simulate the behaviour and engineer the construction of off-Earth structures by adapting the vernacular and contemporary methods widely used on Earth.

Societal and environmental

Automotive, aerospace, and defence industries tend to push technological development by operating in the context of extreme cases and environments. Technologies developed for these industries can find applications in the most diverse sectors such as health, energy, environment, education, mobility, information technology, and commerce. However, in some cases these applications are identified as by-products. If we take the reciprocal nature of off- and on-Earth construction research into account from the start, we might be able to increase the range and societal impact of extra-terrestrial construction.

In the contemporary era, it is widely accepted that on-Earth construction faces many challenges. One urgent demand relates to our environment. As our resources head swiftly towards scarcity, the architectural, engineering, and construction industries are more actively considering circularity and material lifecycles (De Wolf et al., 2020) as a paramount constraint to preserve life as we know it on our planet.

Off-earth, supply redundancy rather than circularity has so far driven human exploration missions (Owens et al., 2017; Owens and DeWeck, 2016). At the same time, due to scarcity of resources and economical constraints intrinsic to human exploration of space, longer presences in hostile environments could benefit from the circularity paradigm. Specifically, the circularity of resources is an emerging topic of future sustainable human exploration, as it relates to the survival and preservation of the human and machine presence in space. For example, ESA astronaut Alexander Gerst recently installed the ESA's advanced closed loop system (2019) on the ISS. It produces water from carbon dioxide, which in turn is used to produce oxygen. Other related emerging fields are the lifecycles and reusability of structural infrastructure. These are also particularly relevant for Earth, where material waste and inefficiencies in the construction industry are linked to a lack of integrated end-of-life strategies (Brütting et al., 2019). Construction materials have traditionally been seen as essentially infinite and of low value when compared with other industries, leading to little emphasis on significant efficiency savings. Another challenge is the high embodied energy of materials such as cement, aluminium, steel, fixtures, and fittings – all multiplied by the massive quantities used and wasted annually. Advances in space research with regards to ISRU, manufacturing, recycling and even regenerative life support systems (Häder et al., 2018) can inform, if not be integrated, with advances in terrestrial construction processes in the future.

Research questions & statement

Given the extreme extra-terrestrial construction conditions – i.e., scarcity of processed structural materials, imports from Earth, machinery, and labour – the architectural and structural design of off-Earth infrastructure will have to be dictated by what is feasible in terms of available material properties and construction methods. This contrasts with the contemporarily prevalent form-centric architectural vision in terrestrial architecture developed often in isolation from structural performance and material considerations.

The off-Earth context is akin to the one that dominated our architectural and construction history for millennia, in which the resulting form of dwellings, landmarks, and infrastructure was largely dictated by the availability and properties of local construction materials accessible to the various civilisations and cultures. For example, the shape of gothic cathedrals is directly related to, and an outcome of, the material properties of masonry and the geometries that can be in structural equilibrium within it (Heyman, 1995). It should be noted that at the time, these shapes were a result of trial and error over long spans of time without their creators necessarily being conscious of their unique geometrical and mechanical properties. In the contemporary context, these have been deciphered, researched, and developed into methodologies that can result in materially efficient structures by taking into consideration the structural performance in the early design phase. This field of research is broadly known today as form-finding.

This innovative subject is thus closely related to traditional vernacular construction and, due to its intrinsic characteristics, can benefit both on-Earth and off-Earth design and construction. In this context we pose the following two research statements.

Firstly, extra-terrestrial structures and architectural visions proposed in the literature primarily focus on continuous monolithic structures, yet their discrete counterparts – as observed on Earth – could have comparative advantages, which may make them more appropriate or robust for early lunar infrastructure.

Such possible advantages include:

- Reusability – if the constituting modules can be recycled for the construction of multiple infrastructure projects, the structural material and subsequent energy spent on constructing them corresponds to multiple uses rather than a single one.
- End-of-life behaviour – if the structures can be fully disassembled and the site left in its initial state after the infrastructure is decommissioned, the phenomenon of empty and abandoned structures, similar to the accumulated space junk currently orbiting the Earth, can be avoided.
- Constructability and repair – if the modules can be fabricated, and repaired, individually using regolith processing methods, component-based structures could minimise their embodied energy and maximise their lifespan through component repair or replacement within the structure.
- Lastly, given possible seismic activity, such as moonquakes, a comparison of the seismic performance of continuous and discrete-element structures would be an additional element of a holistic design for the off-Earth environment. For example, such a study should assess deformation demands imposed by the moonquakes on the structures, to prevent the formation of cracks that could hinder structural durability, safety, and serviceability.

Secondly, whilst we can apply terrestrial structural techniques to other worlds, we can also use advances from extra-terrestrial structures to inform contemporary terrestrial ones. Even though there is a rich history of vernacular component-based architecture and construction on Earth, and of contemporary form-finding, which is increasingly applied to architectural and engineering design, our built environment is predominantly characterised by material inefficiency and a lack of recyclability, as described above.

This can be attributed to the fact that today's capabilities have changed dramatically. In other words, we build inefficient structures because we can afford to – the progress of structural materials and the construction processes at our disposal allow us to detach design from performance, at least at the early stages, and imagine the form in isolation knowing that it is probably possible to construct it somehow. The materially-efficient structures observed throughout our vernacular and masonry construction heritage were directly related to an abundance of constraints which are largely obsolete today. In this context, we can observe how the extra-terrestrial built environment is an extreme, and heavily constrained, case of our present situation, and, remarkably, a very similar case to our past.

Characteristics such as material efficiency and reusability are a necessity when it comes to research and development on the design and construction of permanent extra-terrestrial outposts. This developing body of knowledge can be enriched by our past and, in turn, inform our future, with a focus on energy and waste minimisation in conjunction with maximising material efficiency.

Literature review

On-Earth, component-based, design and construction systems

Over the last few millennia, numerous vernacular design and construction methods have been developed by using predominantly local resources (ISRU) and following structurally efficient geometries as a result of trial-and-error processes.

Many of these methods are based on component-based systems comprising bricks, structural tiles, masonry elements (voussoirs), or topologically interlocking components. These can be observed throughout several historical periods and geographical areas spanning from the vernacular construction of vaults in sub-Saharan Africa and Persia to the stereotomy methods of Gothic cathedrals (Oliver, 1997; Fitchen, 1981). When it comes to brick-based methods, which require mortar but no, or minimal, scaffolding (Fig. 1b), these can be observed in structures such as: vernacular Nubian and Persian vaults (Wendland, 2004); Brunelleschi's domes in Italy (Paris et al., 2020); and more recently, Guastavino structural tile vaulting techniques (Ochsendorf, 2010). Additionally, stereotomy methods, which involve the cutting of 3-dimensional solids such as masonry into specific shapes that can be fit together to form spatial structures, can be potentially mortar-less and in some cases even scaffold-less. These have been applied to the development of structures such as Gothic cathedrals (Fitchen, 1981) (Fig. 1c), Byzantine vaults (Choisy, 1883), topologically interlocking structures for floor slabs (Fig. 1e) (Frézier, 1738), lighthouses such as the Eddystone lighthouse designed by John Smeaton (Fig. 1d), dry-stone constructions, e.g., the walls of the Maya civilisation, and the characteristic dome-shaped limestone trulli dwellings of the Puglia region in Italy (Fig. 1a) (Todisco et al., 2017).

These methods, being potentially mortar-less and scaffold-less, hold promise for the development of extra-terrestrial structural systems where structural material, scaffolding, and binders are sparse and prohibitively expensive to transport from Earth. What is more, mortar-less, component-based infrastructure has the potential for reuse through a sustainable construct and deconstruct cycle in which one type of infrastructure can be converted to another depending on the ever-changing needs of a growing settlement.

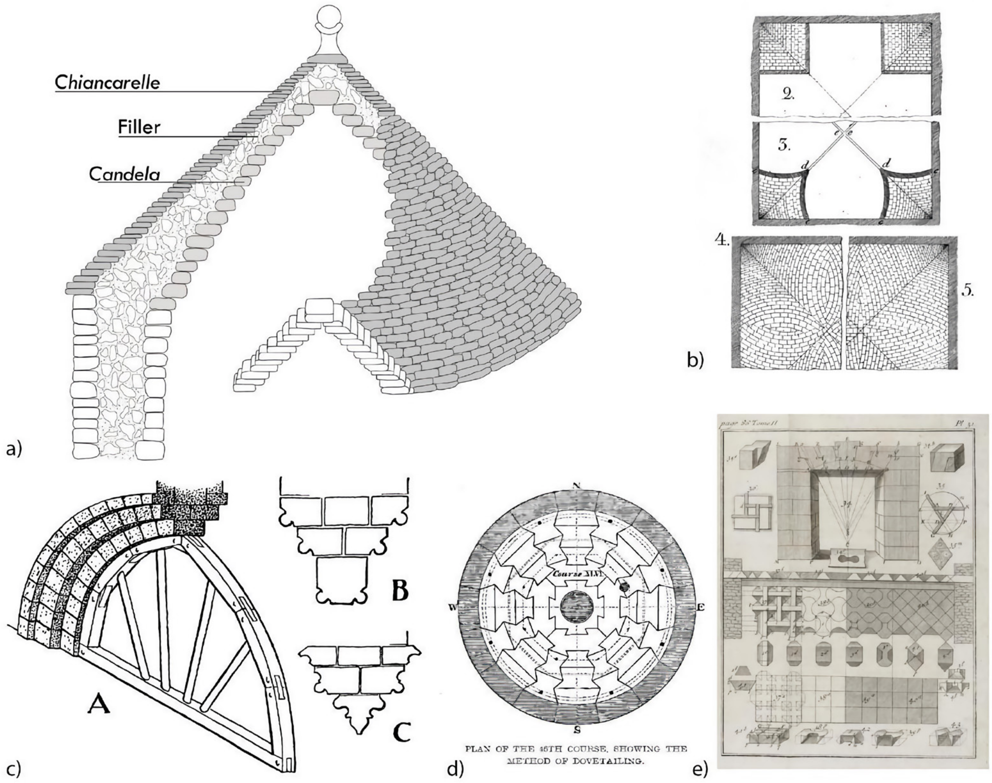

FIGURE 1 a) Dry stone domes as seen in the traditional trulli constructions of Puglia, Italy from Todisco et al. (2017); b) Brick cross vault with self-supporting courses (Wendland, 2004); c) Masonry arch of a Gothic cathedral comprising voussoirs (Fitchen, 1981); d) Masonry lighthouse comprising dovetail interlocking components; e) Flat vaults and floor slabs constructed from interlocking components (Frézier, 1738).

Form-finding frameworks

Form-finding comprises several different approaches and methods but can be broadly defined as "the forward process in which parameters are explicitly/directly controlled to find an 'optimal' geometry of a structure which is in static equilibrium" (Adriaenssens et al., 2014). The earliest – and perhaps most well-known – examples of form-finding are physical models such as chains suspended from two points which result in tension-only structures, and equivalently compression-only arches when inverted (Fig. 2a), similarly 3-dimensional hanging chain models used by Gaudi for the Sagrada Familia form studies (Fig. 2b), 3-dimensional hanging fabric models developed by Heinz Isler for his concrete shell explorations, and soap film structures used by Frei Otto for modelling lightweight tensile structures (Fig. 2c).

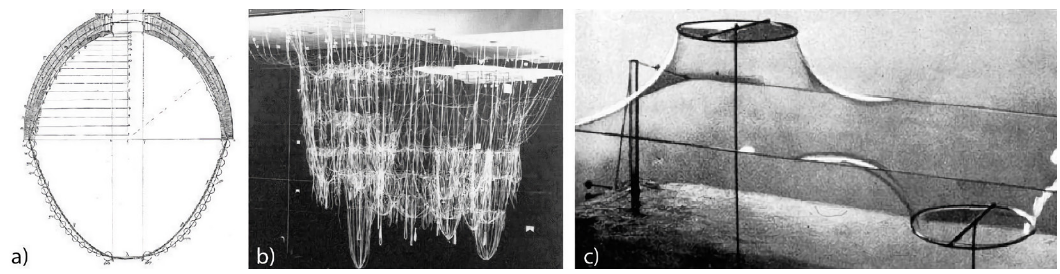

FIGURE 2 a) The geometry of a hanging chain in tension can be used for the safety assessment of masonry structures as depicted here by Poleni (1748) for St. Peter's basilica; b) Spatial hanging chain model used for the form-finding of Sagrada Familia by Gaudi (image credits: Institute for Lightweight Structures, Stuttgart); c) Soap film studies for the form-finding explorations of tensile structures by Frei Otto.

In the realm of contemporary form-finding for structurally efficient geometries, techniques such as dynamic relaxation (Day, 1965) and force density (Schek, 1974) have been proposed. Specifically, by defining parameters such as the boundary conditions and the state of stresses of the structure, it is possible to find the corresponding geometry which is in static equilibrium. As a result, the structural analysis and boundary conditions are the input, and the form is the corresponding output rather than the design preceding the analysis phase. Related examples of application of these methods include the grid-shell of the Great Court Roof of the British Museum (Fig. 3b) which was designed by Foster + Partners and form-found by Chris Williams (Williams, 2001) using dynamic relaxation, and the works of Frei Otto such as the Mannheim grid-shell and the German Pavillion at the 1967 expo in Montreal (Liddell, 2015).

FIGURE 3 The Great Court Roof grid-shell of the British Museum form-found by Chris Williams (image credits: Foster + Partners, Nigel Young).

Component-based structural systems are experiencing a resurgence due to their versatility and lightweight, material efficient nature in conjunction with progress in computer aided design (CAD). When it comes to masonry, the fundamental theory of thrust lines and thrust surfaces has been extensively studied in recent decades, most notably by Heyman (1995). It is experiencing numerous modern-day computational applications through digital stereotomy and robotic manufacturing, which enable the precise design and cutting of the voussoir geometries (Rippmann et al., 2012). Also, research into topologically interlocking components is an active field, specifically their generalisation in doubly-curved spatial structures (Loing et al., 2020). Moreover, academic interest in the subject is reflected in the work of research groups pursuing it and developing prototype structures such as the Armadillo Vault (Block et al., 2017) (Fig. 4a). It was exhibited at the Architectural Venice Biennale in 2016 and comprises robotically-cut, custom made voussoirs which form a shell without the need for mortar. Further example are the long-span shell of the Mapungubwe National Park Interpretive Centre made of structural tiles (Ramage et al., 2009) (Fig. 4b), and the hybrid timber shell structure comprising interlocking components (Mesnil et al., 2018).

FIGURE 4 a) The mortar-less 'armadillo' vault as exhibited at the Venice Biennale in 2016 (Block et al., 2017); b) The long-span shell of the Mapungubwe National Park comprising structural tiles (image credits: Iwan Baan).

These component-based precedents are successful examples of materially efficient and lightweight structures that strive to merge contemporary CAD advancements, fundamental structural theory, structural insight from previous centuries, and in some cases vernacular construction methods. At the same time, they could not necessarily be used in the extra-terrestrial context since they require scaffolding or mortar, or they consist of too many different pieces that cannot be easily reused in other infrastructure types and geometries.

Construction methods

Machines have been used since ancient times to assist people in construction. Iconic historic buildings such as the pyramids, the Colosseum, and St. Peter's Basilica materialised via a combination of sheer manpower and simple yet effective tools. Since the industrial revolution, building construction has evolved significantly in two ways. Firstly, building materials can be mass-produced in factories, which allows for a more efficient and standardised supply. At the same time, there was a slow yet continuous demise in craftsmanship and the use of natural materials. Secondly, advancements in construction machines and technologies led to a significant reduction in the labour required. Buildings became larger and stronger, and the building process faster and more standardised. But when it comes to automation, and specifically to the use of robotics, the construction industry lags significantly behind. This discrepancy presents an untapped opportunity for the construction industry due to the inherent advantages of robotics. Specifically, robotic systems are less dangerous, can work for 24 hours a day without losing focus or making errors, and are unfazed by extreme environments.

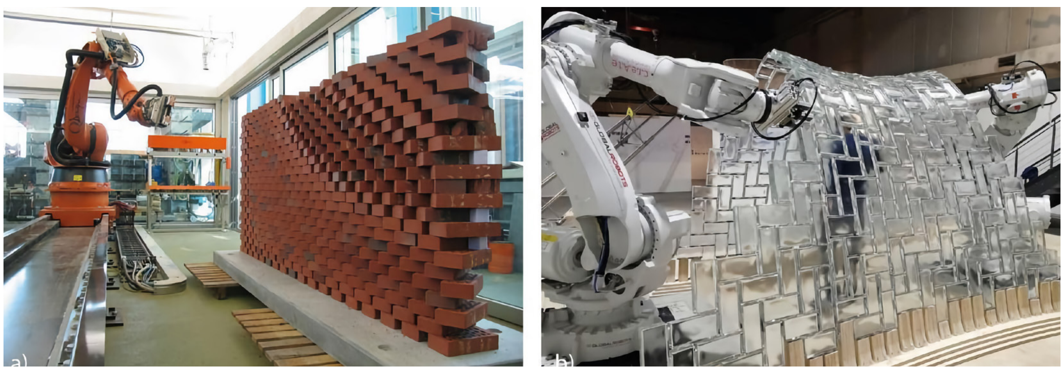

FIGURE 5 a) The Programmed Wall by Gramazio Kohler (Bonwetsch et al., 2006); b) The glass brick vault by SOM, TU Delft, and Princeton (image credits: SOM).

Robotics

Applications and built prototypes of robotically assembled component-based systems include the Programmed Wall (Fig. 5a) by Gramazio Kohler research of ETH Zurich (Bonwetsch et al., 2006) and the glass brick vault (Fig. 5b) by SOM, TU Delft, and Princeton (Parascho et al., 2020). In the former, the bricks are placed in precise and predefined locations by a fully automated robotic system. This methodology can allow for the construction of brick walls with geometries that would have been prohibitively complicated by means of human labour. At the same time, glue used in the interface between adjacent bricks prohibits their reusability, whilst the possibility of varying the dimensions of the bricks in conjunction with the robotic capabilities has not been investigated. The latter is a collaboration between human and robotic labour in which humans perform complex tasks that require adaptability, such as placing mortar between bricks, and the robots perform precise and laborious tasks, such as placing the bricks in their predefined locations. Operating in complex environments such as on the Moon and Mars requires robotic systems characterised by autonomy and redundancy. One solution proposed to increase redundancy is multi-robot systems or robotic swarms, collectively interpreting their environment and displaying emergent behaviour through a simple set of rules. In the context of remote, extra-terrestrial construction, Foster + Partners has proposed the idea of an autonomous robot swarm that can use indigenous materials to build protective shells (Fig. 6a) (Wilkinson et al., 2016b). Other recent advances in robotics pave the way for a potentially robust technical framework that could allow for off-Earth construction. Specifically, these include the capabilities of the Spot robot – developed by Boston Dynamics – in uncalibrated terrains and (Fig. 6b) of swarm robotic systems in assembling brick-based systems (Werfel et al., 2014) (Fig. 6c).

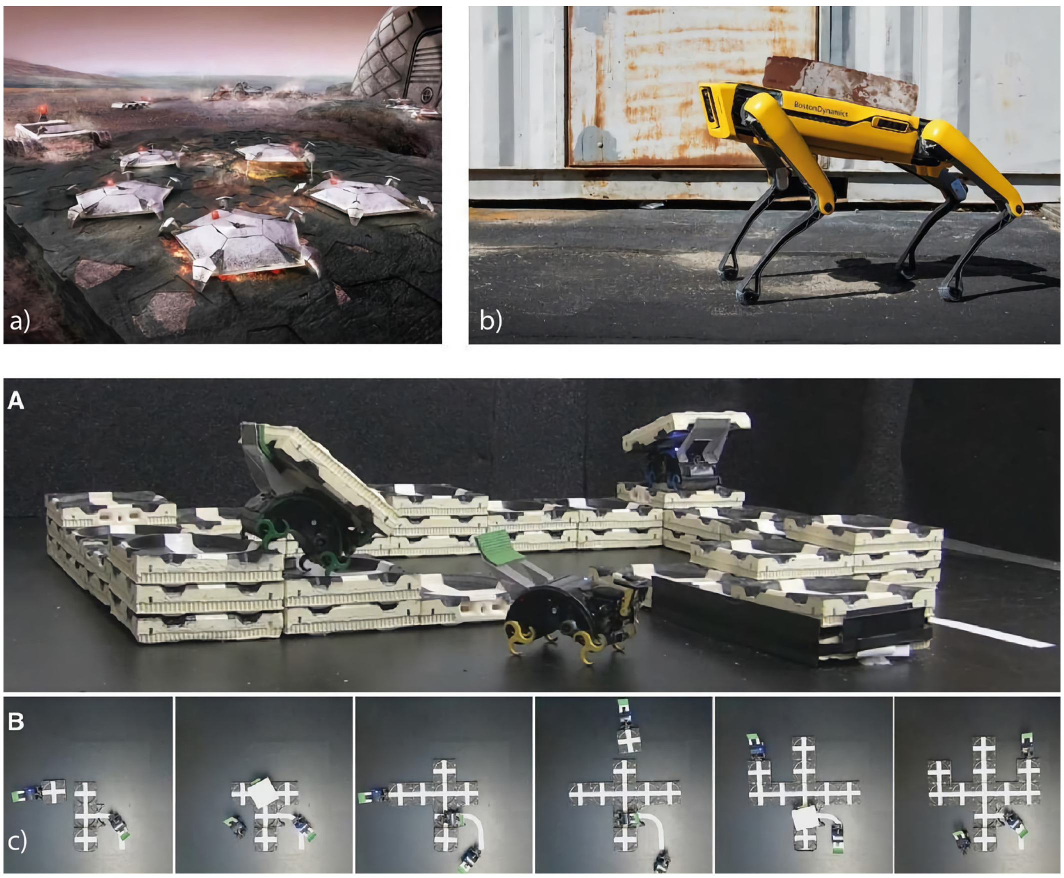

FIGURE 6 a) Foster + Partners NASA 3D Printed Mars habitat concept showing power-beaming to a robotic swarm of microwave regolith sintering (Wilkinson et al., 2016b); b) The Spot robot developed by Boston Dynamics could potentially be used for transferring and assembling bricks on uncalibrated terrains; c) Self-organising robots working like termites can build structures independently (Werfel et al., 2014).

Off-Earth design

Engineering proposals

The design of off-Earth structures has been studied by numerous researchers over the previous decades from a structural engineering point of view (Kalapodis et al., 2020). The proposed solutions span a wide range of different methods: from inflatable habitats, to rigid deployable structures, and 3D-printed domes. These studies provide valuable insights in terms both of possible extra-terrestrial structures and of their subsequent structural analysis and performance given the specific harsh environmental conditions that they will need to withstand. At the same time, if we assess them from a sustainability perspective – in terms of their reusability – they mainly investigated monolithic or continuous structures which cannot be easily disassembled and recycled for other infrastructure, while also not allowing for flexibility and geometric adaptability. As a result, locally sourced and produced structural materials, energy consumption during construction, and imported materials from Earth correspond to only one extra-terrestrial structure and cannot contribute to the construction of other infrastructure. Moreover, these approaches concern predominantly simple geometries such as circular barrel vaults, cylinders, and parabolic arches, thus limiting the architectural vocabulary and array of possible functions.

Architectural proposals

The speculative architectural design of off-Earth structures has drawn renewed attention in recent years (Mueller et al., 2019). Particularly, structures such as habitat shells have largely monopolised this attention due to their expressive, organic nature. Specifically, and in the lunar context, recent contributions include: 3D-printed monolithic vaults designed by Foster + Partners (Fig. 7a) utilising an optimised structural material distribution based on bone formation (Cesaretti et al., 2014); 3D-printed infrastructure of toroidal structures designed and developed by NASA, BIG, SEArch+, and ICON (2020) (Fig. 7c); and an inflatable moon village (2019) jointly proposed by SOM, ESA, and MIT (Inocente et al., 2019) (Fig. 7b). In the Martian context, architectural proposals include: the 3D-printed Mars Ice House from SEArch+ (2016) (Fig. 7d); 3D-printed monolithic vaults designed by Foster + Partners, which employ a swarm robot system to print the structure in layers (Fig. 7e) (Wilkinson et al., 2016b); the 3D-printed Mars habitat domes from AI space factory, who developed the MARSHA Architecture on Mars (2018) project (Fig. 7f); and the habitat structures proposed by Hassell studio (Fig. 7g) in the context of the NASA 3D-printed habitat challenge (2018). All of these approaches comprise continuous monolithic structures that are not suitable for reconfiguration. As a result, there is scope for the development of methodologies that take recyclability into consideration for the design of extra-terrestrial infrastructure.

Component-based systems

Component-based structural systems have already been proposed in the extra-terrestrial context. In particular, Dyskin et al. (2005) and Imhof et al. (2017) studied the potential of topological interlocking elements. Specifically, the RegoLight project focused on component-based infrastructure (Fig. 8) composed of interlocking tetrahedral-based elements (Imhof et al., 2017). These approaches resulted in a potentially mortar-less and scaffold-less construction process and apply to planar elements such as walls, and standard curved geometries, such as barrel and corbel vaults.

However, the range of applicable geometries is limited, as is the potential for reuse. This is because a departure from the applicable geometries would require scaffolding and numerous different brick geometries. This hinders the reusability potential of the infrastructure, because bricks designed for spatial, curved infrastructure geometries cannot be easily reused for planar ones. This is an inherent issue in stereotomy approaches in which the geometry of the brick is fully dictated and in return fully dictates the global geometry. Thus there is little versatility in terms of reusability.

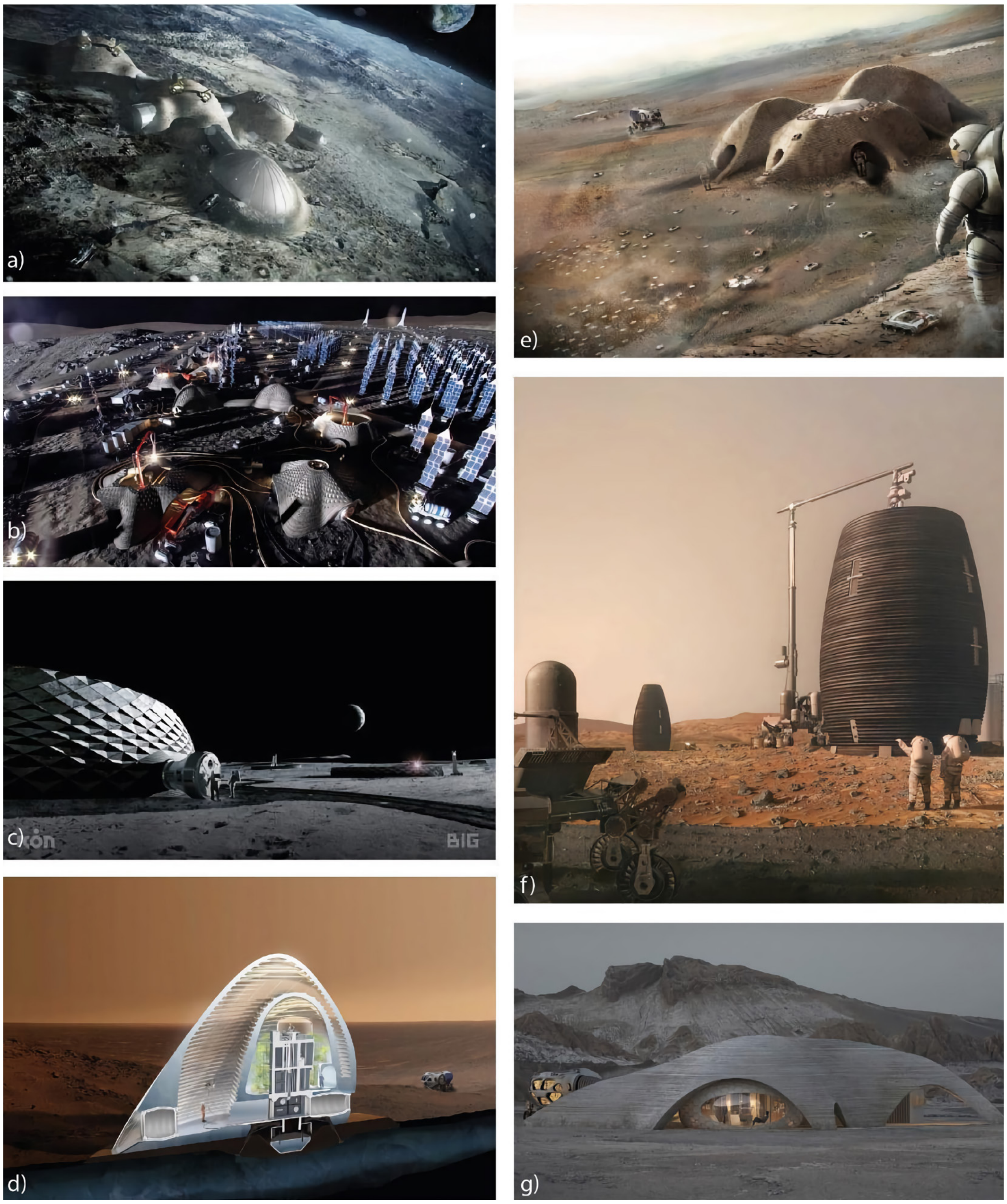

FIGURE 7 a) Lunar 3D-printed monolithic vaults designed by Foster + Partners (image credits: Foster + Partners); b) Lunar village designed by SOM (image credits: SOM); c) 3D-printed lunar infrastructure designed by BIG and ICON (image credits: BIG and ICON); d) Martian 3D-printed habitat (ice house) developed by SEArch+ (image credits: SEArch+); e) Martian 3D-printed monolithic vaults designed by Foster + Partners (image credits: Foster + Partners); f) Martian 3D-printed habitats designed by AI space factory (image credits: AI space factory); g) Martian 3D-printed habitats designed by Hassell studio (image credits: Hassell studio).

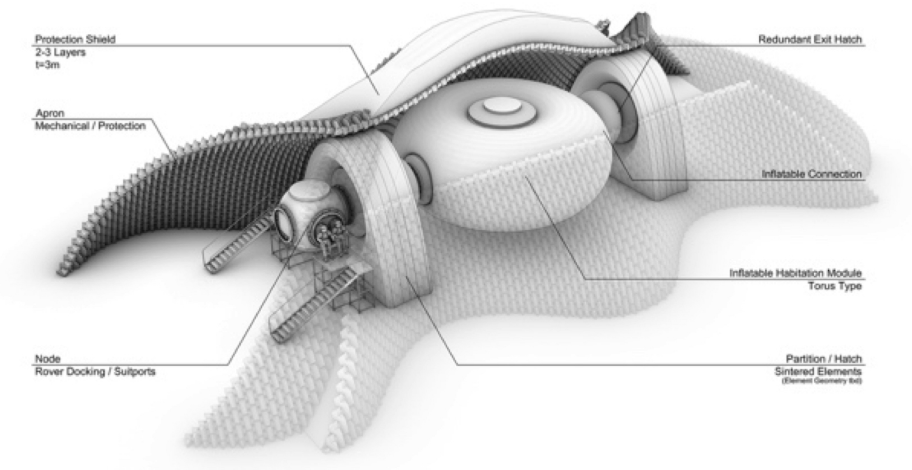

FIGURE 8 Habitat geometry comprising interlocking components as suggested by the RegoLight project (Imhof et al., 2017).

Innovation of proposed design and construction system

Within the literature and canon of works envisioning off-Earth structures, there is a strong tendency towards continuous structures constructed using additive manufacture, including in our own previous proposals for lunar and Martian habitats. And yet, discrete structures have certain clear advantages that may make them more amenable to the immediate task. By discrete structures, we refer to those which do not behave monolithically due to being composed of many smaller elements, i.e., bricks, blocks, or tiles, and minimal use of binding. As discussed in previous sections, bricks, tiles, and stone blockwork have a long history on Earth, influenced by parameters such as available materials, processes for hardening, ability to form or cut, and handling. Their use has run parallel to continuous structural methods, like wattle and daub, rammed earth, and concrete.

We suggest that a component-based (Fig. 9b), rather than continuous (Fig. 9a), approach to designing and constructing extra-terrestrial structures could be beneficial in terms of maximising the sustainability of space exploration and permanent human presence beyond our planet. This design methodology is based on identical components that interlock via a system of grooves on their bottom side and a system of pins on their upper side. In this way, the component shape does not define, and is not defined by, the global geometry of the structure as in the case of stereotomy techniques. Moreover, the assembled configuration contains within its geometry a form-found compression-only surface, thus maximising material efficiency by minimising tension and bending. In particular, the proposed design and construction paradigm is underpinned by the following principles:

- Reusability: This will be achieved by developing mortarless design systems based on the interlocking properties of adjacent components. In this way, the system compensates for the lack of mortar and binders, which can hinder reconfigurability. As a result, the first unique advantage of discrete systems is their potential for reuse over time. Structures exist to serve a function, which may change or cease over the course of a settlement's lifetime. Discrete bricks can be deconstructed and reconfigured into new structures with some ease. Moreover, in the same fashion as some vernacular examples of dry-stone construction, the design of the components should be generic – one geometry that can be used for multiple configurations and uses – rather than specialised in terms of where the component is placed within the global infrastructure geometry.

– Efficiency: This will be achieved by using form-finding techniques which can derive global geometries in structural equilibrium with specific mechanical properties – e.g., compression-only doubly curved shells. In this way, the generated infrastructure forms comply with, and are a result of, the properties of the available ISRU structural material, which as suggested from the relevant contemporary literature will be adequate mostly in terms of compression strength – similar to vernacular brick-based vaults, dry-stone domes, rammed earth structures, and masonry cathedrals. Also, since the structures will not be monolithic, replacement and repair could take place in a component-based fashion without jeopardising the serviceability of the whole infrastructure.

– Economy: This will be achieved by using each component, and hence its corresponding material and fabrication energy, not only for multiple structures within its lifespan but also for other uses during construction - e.g., temporary scaffolding during erection. What is more, as showed by both vernacular analogues and contemporary research (Imhof et al., 2017), interlocking, component-based systems hold the promise of minimising the need for scaffolding, if not making it obsolete, showing the potential of free-standing structures during erection, and hence unsupported overhangs. This allows for overhanging features such as arches, domes, or slopes. Furthermore, the decommissioning of structures and evolution of the human outpost will not result in abandoned ruins, unusable structural material, nor, ultimately, in the permanent transformation of the lunar and Martian landscape.

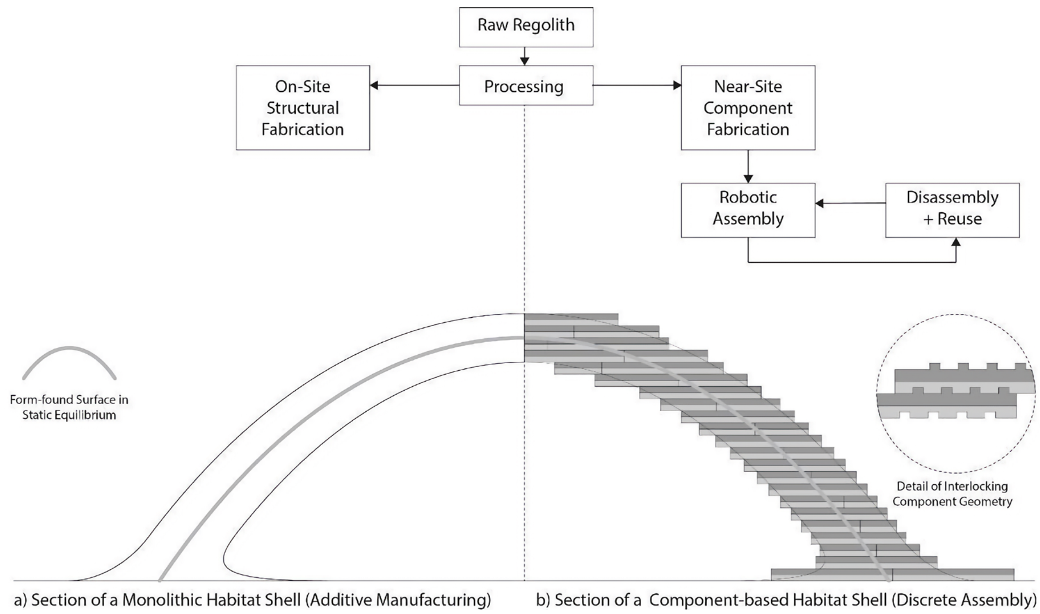

FIGURE 9 a) Section of a monolithic 3D-printed vault that cannot be recycled; b) Section of a component-based, mortar-less and scaffold-less vault, the components of which can be reused.

Lastly, bricks offer the strong benefit that they, due to their small size, can be fabricated in a controlled environment (e.g., thermally or atmospherically). This does not preclude additive manufacture use for bricks, which may be preferable for the robots and tools in a controlled or semi-controlled environment such as a pressurised workshop. Similarly to continuous structures, discrete systems can also achieve adaptable and complex forms. We need only look to the wide range of applications and creativity of brick structures found on Earth.

Conclusions

In this research paper, we proposed that a component-based design methodology may hold comparative advantages over its continuous counterparts, which currently dominate the literature and architectural discourse of off-Earth design. Specifically, we suggested that this system could be based on a synthesis of ancient vernacular and cutting-edge form-finding knowledge on structural design and construction. We discussed how extra-terrestrial infrastructure design has striking similarities with the past and present tradition of the built environment in the Earth context and suggested that it should be seen as an extreme case of our design and construction practises on Earth rather than as an isolated field. Moreover, we put forward a bi-directional relationship, in which off-Earth construction acts as a catalyst for change here, and on-Earth structures as a precedent for lunar and Martian construction. In this context, we highlighted how industries on Earth have much to learn from the extreme constraints characterising space missions. These lessons could lead to structures that are not only lightweight yet strong but also environmentally efficient and recyclable.

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