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Applied Space Architecture

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Throughout history, there has been a practical relationship between space-derived knowledge and architecture discipline. 'Applied space architecture' concept is based on applying its approach to terrestrial processes from an architectural standpoint. Accordingly, this paper poses a line of thought, that not only can contribute to solving present and future energy issues down on Earth, but it also can benefit the space industry.

Nomenclature

AIAA = American Institute of Aeronautics and Astronautics
ATV = Automated Transfer Vehicle
BIM = Building Information Modeling
CHP = Cooling Heating Power
ECLSS = Environmental Control and Life Support Systems
ESA = European Space Agency
ISRU = In Situ Resource Utilization
LEO = Low Earth Orbit
NASA = National Aeronautics and Space Administration
TIM = Transparent Insulation Materials
VIP = Vacuum Insulation Panel

I. Introduction: Cosmos, Architecture and Challenges

Back to the Middle Ages, some of the knowledge upon which current space exploration was based, was already applied to architectural works. Since its dawn, this discipline has been related to the study of the cosmos, as many ancient constructions have shown us, for instance: *Goseck* Circle[1, 2] (Germany, 4900 B.C.) the world oldest observatory. Nevertheless, during the Eastern Roman Empire (Byzantine Empire) the architectural discipline looked at the cosmos from a different perspective; the 'Mechanikoi'[3] degree was given to those architects whose knowledge was beyond the skills needed for construction on Earth, beyond the *arkitekton*[3] or constructor. Their background as professionals made them well versed in mathematics, physics or astronomy, apart from traditional architectural disciplines[3]. These *mechanikoi* (*mechanopoioi*[3]) established a connection between construction and space related subjects, this scientific knowledge, lead to current space exploration technologies. Beyond theory, they put their perspective into practice, as Hagia Sophia (*Holy Wisdom)* shows us (Istanbul, 537 A.C., Fig. 1 and 2). This former cathedral was designed by two *mechanikoi*, Anthemius of Tralles and Isidore of Miletus who applied their concepts to show, not only the image of Byzantine cosmology[4] (earth-dome), but also a very advanced structural design and construction proficiency. They even established a link between the early stages of robotics and architecture, as we can see in Heron of Alexandria's works[3] (e.g. flying thrones in Theophilo's court).

To think about inhabited environments in space[5] will take some centuries; nonetheless, those 'proto-space architects' and current professionals have resemblances: both of them connect architecture either with scientific disciplines or with space technologies. In fact, both of them developed complex Earth-based projects related to space, whether it was through cathedrals or analogues in Antarctica.

In modern history we can find some other applications of aerospace knowledge to architecture and *vice versa*. The industrial revolution brought some of the first thinkers who sensed the world like a spaceship[6] (Fig. 4), by the middle of the last century, architects like Buckminster Fuller applied aerospace construction techniques to his *Dimaxion* houses[7]; he used aluminum strained structures as a way to reduce the cost of housing (less mass = less price). However, these connections also lead to the beginning of space architecture (Skylab) back in the 70s.

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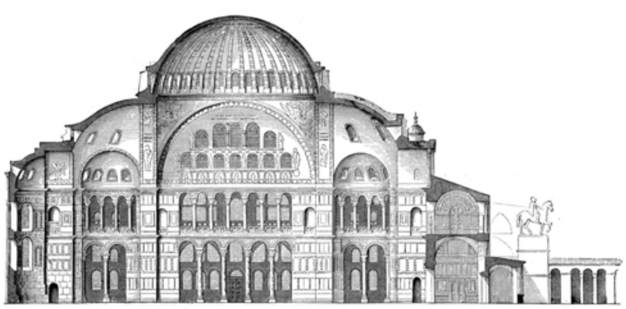

Figure 1. Cross-section of Hagia Sophia[42] (reconstruction)

Nowadays, several main issues like overpopulation (9 billion people[8] by 2050), global sustainability policies, social and economical matters[9] or eventual climate changes[10] influence the way we generate, use and manage *energy* in our environments. On Earth, buildings are one of the largest consumers of resources, therefore 'next-generation' architecture is a fundamental pillar of the upcoming economy we are facing[12, 13]. In other words, we are looking for more sociologically and environmentally responsible architecture[14].

Furthermore, space industry is in the beginning of a new era in its development; space tourism is becoming a reality, and small private space firms are spreading. An increase in human spaceflight missions will foster architectural approaches to the sector (public or private). However, the connection between these two areas is taking another direction as well, for example: NASA is not only committed to solving environmental[31] challenges (energy, water...) but it is also engaged with initiatives like *Sustainability Base*[15] (Ames Research Center), a high performance building devoted to direct technology transfers into terrestrial architecture. This line of work seems to be well suited for space architects, because applying these technologies and concepts to Earth constructions requires an approach that deals with multiple aspects (cultural, technical, aesthetical, etc.)

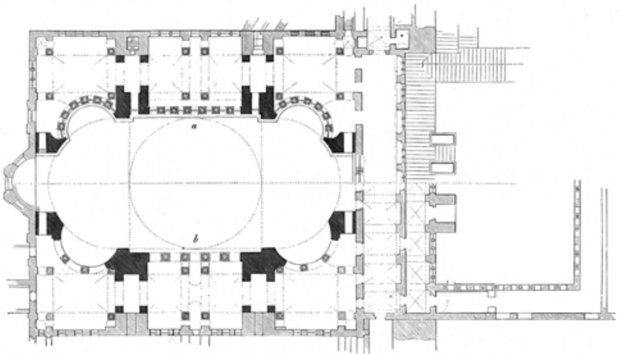

Figure 2. Floor Plan of Hagia Sophia[42]

To go in depth into these links, can benefit society in many ways, hence this paper researches current energy issues on Earth that show likely connections with space architecture. To apply a space architecture approach on terrestrial processes entails, on the one hand technological and conceptual spinoffs that can influence projects on Earth. On the other hand, they could become a source of data, experience and knowledge for the space sector as well.

To elaborate upon this concept of 'Applied Space Architecture', it is necessary first, to establish the way to study these relations between sectors. We can outline three main areas: *energy (power)*, *materials* and *design;* a fourth one, *education* is embedded in each one of them. This paper focuses on the first one, addressing present and near future challenges. In order to do so, it differentiates between *process and project*:

'Project' is a key concept in architecture practice (*project[18], noun - a piece of planned work or an activity which is finished over a period of time and intended to achieve a particular aim*). However, this 'problem-solution' approach can have a more versatile perspective as a 'process'[18] (*noun - a series of actions that you take in order to achieve a result*). This process point of view engages the architectural project in a more dynamic way: while it addresses the main requirements, it also introduces complementary variables. For example, a housing project requests solution to some well know architectural issues, such us client preferences, planning question or regulations. Besides them, we could add other questions: a possible adaption for different future uses, or some new technologies, which not only solve actual problems but they also could benefit other sectors. Example 2, will elaborate this synergy.

II. Energy Challenges

From an energy standpoint, human constructions certainly pose many architectural challenges on Earth. World electricity generation will increase 77% from 2006 to 2030[21], and they are responsible for 40% of energy consumption and 36% of CO_2 emissions[22] in Europe. In the USA, they consume 72% of the total electrical power[11]. Consequently, architecture is the biggest energy consumer sector. Energy needs are increasing, due to overpopulation, new requirements and more demanding comfort standards, so they force us to think about new energy sources and strategies. Sustainability and clean energy implementations are, indeed, issues that current technology trends need to face.

In space, constraints[27] for architecture, both in LEO or on planet surface, are quite severe and require key technologies to allow human life on space. In addition, 'vehicular'[28] space architecture must be autonomous from an energy point of view, not an easy achievement due to these constraints, isolation and distance from Earth. Nowadays, energy autonomy is still being developed, as ISS shows (Fig. 4): it still needs for its attitude control engines, propellant brought from Earth (ATV assitance[29]). In the end, the more we inhabit space the more efficient and reliable those energy sources have to be.

Nonetheless, Earth-based space architecture represents an actual connection between these two architectural environments, for instance: analogues[30, 31], simulators[32, 33], support facilities and spaceports[20] already offer a great opportunity to deal with the application of space architecture approach to Earth processes in depth.

Besides the projects which directly connect space and Earth segments of space programs (public or private), the technologies and protocols we need to face energy challenges are constitute the base to establish new connections between space and Earth architecture as *Table 1* summarizes and the following points develop:

A. Active Systems: Energy Generation Technologies

These systems tend to work on a little scale and a local range, allowing dwelling settlements to be increasingly independent from a traditional power grid[23]. These decentralized systems also entail a combination of clean energies and multi-source systems. The small-scale building becomes a 'micro' power station that uses 'on site and near site' resources[23], through a combination of:

- *Different sources*[25, 26] such as solar power, solar thermal power, fuel cells (hydrogen), biomass, geothermal or micro hydropower systems among others
- *Different technologies*[25]: micro turbines, CHP[24] (micro-cooling, heating, power and thermally activated components), batteries and backups systems, hybrid systems integration, etc

Space architecture formulations share most of these sources (solar, fuel cells) and technologies, therefore to establish links and common developments between them will bring more affordable solutions in space and on Earth. Current trends, such as US *smartgrid*[23], pursue same energy autonomy designs, as long-term formulations do, working on small scale with on site resources.

On the other hand, dwelling environments depend on multiple technologies: in space, Environmental Control and Life Support Systems (ECLSS), Thermal Control Systems (TCS), among many other systems demand efficient and stable energy sources in order to live there. On Earth, there is also an increase of highly efficient technologies for environmental comfort (heat, cold, humidity, lighting) as well as many new consumer technologies (computers, TV, etc.) that have become a part of our everyday services (e.g. Internet).

This dependency on multiple technologies, which consume significant amounts of energy, requires more power efficiency with a global perspective. Consequently, the habitat, wherever it is, becomes a high performance system by itself regarding energy generation, like those systems within it.

B. Passive Systems and Design Techniques

Besides active technologies, this is a crucial area to reduce energy consumption. Materials and techniques improve the building envelope, the habitability of the inside as well as they allow better energy efficiency. Quoting some of them: advanced transparent isolation materials[25] (TIM), vacuum insulation panels (VIP), low-energy techniques or bioclimatic concepts are good examples. Moreover, these passive techniques and advanced materials, new trends in architectural design pose interesting research lines for future space systems, such as: joint-less architecture (e.g. solar pebble[34]), high-tech green architecture in combination with ancient techniques (e.g. sustainable earth sheltering) or advanced building sustainable simulations using Building Information Models (BIM). Space sector also has to offer powerful tools to contribute to, like systems engineering protocols, or innovative research (robotics, inflatable systems, etc) for better energy functions.

These concepts offer a common area to future class II/III space habitats, which will also use in situ resources (ISRU) for its construction and energy generation and which will become energy autonomous formulations in long-term missions. Energy challenges are also, about how we construct, simulate and maintain these advanced environments. Extreme temperature conditions, as well as isolation from Earth make space environment a unique test bed for advanced insulations techniques and self-sufficient energy systems. On the other hand, lightweight aerospace materials such as *aerogel (Fig.3)*, represent significant advances and actual spin offs on Earth, for instance: *aerogel* insulation strips[35]. One way or the other, these spinoffs and techniques, when they are implemented from an architectural perspective, will contribute to ‘next generation’ dwellings on Earth and in space.

C. Energy Management, Technology Integration and Human Resources

In addition to the combination of several active technologies and passive techniques, an advanced management is required for better energy efficiency. Even as space architecture requires integration of many more systems and variables than terrestrial architecture, ‘next generation’ architecture processes on Earth also require more complex solutions than ‘traditional’ projects to date.

In both fields, combination of high performance systems and passive techniques demand an *architectural perspective* within the design process. Mobility, technology integration, interactivity[15] or energy autonomy concepts are common to both of them. Architectural and design principles (human factors) should not be pushed into the background in inhabited environments, to inhabit any location there must be a balance between habitability and requirements in the process (aside from research missions/projects).

The capacity to endure with regards to energy, is a key concept for space inhabited environments (as well as water, waste, materials, etc.) Space agencies and industry have shown their increasing concern about sustainability[36] issues down on Earth too. Support facilities, labs, factories or spaceports can perfectly be flagships to these concepts. For buildings on Earth to be more energy sustainable, it is essential to implement better protocols and technologies. Besides known aerospace technology spin off[37], there are also applications of space technologies in architecture as a whole, for instance: NASA Sustainability Base[16]. This building is also assigned to become a center for direct transfers between fields.

Space architecture multidisciplinary approach, can contribute very much to energy architectural challenges on Earth. Due to its contact with scientific and engineering research, this discipline can provide a solid base for future advance environments[17] on Earth. An approach that points out that the ultimate relevant link and most valuable resource are the *human resources*. Not only ‘space architects’ but also those professionals directly involved with innovative architectural work in these spheres are a unique asset because of two reasons:

- Their multidisciplinary background, and a problem-solving methodology for issues with no precedents
- They used to dealing with both architectural and technological requirements and constraints

Table 1. The table summarizes common areas between space and terrestrial architecture regarding energy. Each row shows similar subjects or potential links from one area to another, under several topics.

	SPACE ARCHITECTURE	TERRESTRIAL ARCHITECTURE
Active Systems	**High performance systems**	
	Human life in space requires energy consumption from active technologies (ECLSS, TCS, etc.)	Dependency on comfort standard and consumer technologies
	Efficient and stable energy sources (Solar, Fuel Cells...)	Similar energy sources and generation technologies
	Energy autonomy	
	Long-term space architecture formulations	Small scale building as a autonomous energy system
Passive Systems	**Insulation**	
	Unique test bed (e.g. extreme temperature)	Transferrable techniques (e.g. joint-less architecture)
	Aerospace Spinoffs (e.g. *aerogel* insulation strips[35])	Advanced materials and concepts (e.g. TIM)
	Local resources	
	Class II/III habitats would use in situ resources (ISRU)	Ancient architecture techniques (e.g. earth sheltering)
	Passive Design Techniques	
	Advanced innovative tools (e.g. systems engineering process)	Advanced architecture design trends (e.g. BIM)
Management	**Systems integration (formulations)**	
	Integrates many more systems and variables	Next generation architecture requires complex integration
	Balance between habitability and requirements	New energy protocols and concepts are needed
	Architecture Perspective	
	Earth-based space architecture is an actual connection (e.g. support facilities or spaceports as flagships to these concepts)	Mobility, technology integration, interactivity[15] or energy autonomy within architectural standpoint
	Sustainability (process)	
	Space agencies and industry shown an increasing concern	Applications of space technologies in architecture (e.g. NASA Sustainability Base[16])
	Human Resources	
	'Space architects’ multidisciplinary approach in contact with hard science and space technology	Professionals directly involved with innovative architecture

III. Processes

In order to put into practice this perspective, we can consider two lines of work to implement architecture processes. Through this standpoint, we could apply space architecture approaches upon terrestrial processes:

A. Aerospace Technology Spinoffs

The first one is based on applying *aerospace technology spinoffs* in everyday projects, from an architecture standpoint. Since buildings are the biggest energy consumers, its professionals must be a part of this byproduct process, so they can contribute to integrate them into the complex reality of current architecture (cultural aspects, styles, etc.) as well as to find new niches, for instance:

Example: Architectural integration of an aerospace spinoff

Figure 3. Aerogel supporting a brick. Courtesy NASA/JPL-Caltech

To integrate advanced solar cells[38] into the design process represents a chance to improve their implementation. To monitor the process since researchers develop the technology, until it is applied as a commercial product, allows us to introduce it in a way far more valuable to designers and consumers. Consequently, this reinforces the public perception that space research was the source of that appealing and effective solution (space awareness). Furthermore, it also sets protocols for future connections between sectors, as well as it tracks important architecture variables.

B. Space Architecture

The other method is to apply *space architecture approaches* as a whole. If we had been constructing autonomous architectural systems for the last 200 years, we would already have solved some of today's energy challenges in space, as well as down on Earth (example 2). Thus, we can set two scales:

- Habitat unit (small scale)

We can consider the single dwelling as the minimum habitation unit in urban planning. This future autonomous unit would be independent of the power grid and other distribution lines (water, gas, etc.) They have a small size and a predominant function (e.g. housing).

- Complex unit (medium and large scale)

Urban development or small villages are good examples of this scale. This unit entails more people but especially a more complex programme. Hence, a lunar outpost or a space station would be in this category, not because of its size but its complexity (ECLSS, research activity, dwelling, stowage, communications, etc.) The following example elaborates this concept:

Example: Applying space architecture approach to a housing process

Figure 4. International Space Station. Courtesy of NASA

Let us consider a complex unit, for instance a new housing development in a research facility with several labs, residences for researches, stowage area, energy generation systems, etc.

In order to turn this unit into a high performance energy autonomous system we have to integrate different technologies and energy sources into its design, construction and management. Introducing space technologies and concepts would broaden the project. The project becomes a process, when it can also serve to space research purposes. While it could share some aspects with near future space habitats, several key elements would be included, such as:

- Protocols and technologies that poses common areas of research
- Passive techniques, for example earth sheltering techniques in combination to deployable parts can improve energy designs as well as construction protocol developments
- Management and design protocols suitable for future high performance processes

Nowadays there are already actual developments that research 'zero-net' concepts, such as: Malmö[25] city, FortZED[23, 39], Beddington Zero Energy Development (BedZED) (Fig. 5) or NASA *Sustainability Base*[16]. This last one will be a precedent that already uses space technologies for architectural purposes.

Bigger size and more complex programme could help to distribute initial high costs among more agents and functions. On the other hand, it is better to have more than just one building or function in order to study future interactions. As a result, it would be a complete architectural project that fully serves its function (the facility was being used), but also an architectural process that could allow us to gather valuable sources of data.

Figure 5. Image of BedZED[41] (UK) . The project uses only energy from renewable sources generated on site

Through its implementation, we can study within space sector:

- The *evolution over long periods in time* of those energy protocols and techniques: how different technologies work together during an extensive period, and how they last. Their standards are not the same as those of space programs, although their materials, interactions, protocols and software could be the same.
- We can infer conclusions and data for long-term systems without the big costs of bigger and exclusive function projects such as simulators.
- It could help to develop cheaper and more sustainable processes.
- We can study the interaction between technical areas, design concepts, human factors, and multiple working functions over long periods. This also means we could study how those protocols and designs could be updated to address future uses, etc.

Regarding the architecture practice, we can study as well:

- How the process contributes to improve Earth architectural systems.
- How it contributes to create a social awareness over the importance of space research. People could ‘touch’ these technologies while they solve architecture issues down on Earth, increasing the sense of the practical value of space programs in society.
- These processes will also foster multidisciplinary education with practical applications between sectors.
- We can also apply the same points within space sector to this sector.

Therefore, the process works as a mockup for the concepts and protocols themselves. Future space outpost or high performance developments on Earth could have a solid base regarding how several energy sources work over time, their interaction with everyday uses or the way its software must be developed. Virtual construction software, like BIM technologies pose a practical way to study and research this approach, before they could even be built. Nevertheless, we can establish these kinds of processes to urban development, which seek for higher efficiency, outside the space field. The application of this approach, as the *mechanikoi* example shown, can also stimulate creative architectural solutions for these new areas of architecture in space or on Earth.

IV. Conclusion

The kind of processes described, could contribute to current energy challenges, while they benefit both sectors:

- They broaden space architecture field on Earth with other areas that could work as test beds for space industry. Data related to energy generation technologies, technological interactions and their relations with human factors or future adaptability for other uses could extend protocols for long-term missions. In essence, they are a usable mockup for future concepts and complex systems connections over time, for instance: a housing architecture process that implements space architecture technologies and protocols.
- Space architecture approach could also help to deal with energy architectural challenges on Earth, as well as it connect this discipline with advanced scientific and technology areas. In fact, these processes are based on common areas with 'next generation' architecture, such as active and passive systems integration, management, human resources or advanced design trends concerning energy.
- These processes provide complementary concepts to inhabit extreme and new environments like space, as well as those more traditional in a better way. Consequently, they strengthen awareness over the importance and pragmatism of space programs among the public, with solutions that could be "touched". Thus, it benefits society in general terms, contributing to solve present and future challenges through a multidisciplinary approach: ***let us bring space to Earth, so we can keep sending Man to space.***

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