Space Architecture – Theory and Educational Strategy

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This paper proposes a strategy for Space Architecture education based on joint research performed at the International Space University (ISU) in Strasbourg and at the Faculty of Architecture of the Czech Technical University (CTU FA) in Prague. The proposed strategy arranges a Space Architecture curriculum according to the Universal Architecture theory i.e. connecting space and terrestrial architecture disciplines for the benefit of both.

Nomenclature

CAD	=	Computer Aided Design
CTU FA	=	Czech Technical University Faculty of Architecture
CRM	=	Crew Resource Management
ECLSS	=	Environmental Control and Life Support System
EDL	=	Entry Descent Landing
HMI	=	Human Machine Interface
ISRU	=	In Situ Resource Utilization
ISU	=	International Space University
LEED	=	Leadership in Energy and Environmental Design
SA	=	Space Architecture
SICSA	=	Sasakawa International Center for Space Architecture
UA	=	Universal Architecture

I. Introduction

Recent research on human workforce in the space industry identified a demand for specific soft skills which are inherent in the architecture profession (see Appendix I.). A worldwide survey on Space Architecture (see Appendix II.) was started in April 2009 and over a period of 3 months data was collected from an online questionnaire distributed amongst space architects. This survey yielded a number of highly valuable outcomes which led to further research on space architecture education and theory.

The research at CTU FA looks at issues which terrestrial architecture will have to deal with in the 21st century and how space technologies or Space Architecture could contribute to mitigating problems on Earth mostly linked with sustainability and more effective development in both terrestrial and Space Architecture disciplines (see Appendix III.). Alongside the practical technology transfer possibilities and space spin-offs, theoretical research has been performed on the classification of both terrestrial and Space Architecture and their common design principles. Both areas are being classified in one supra-branch named “Universal Architecture” which aims to identify fundamental points in architectural design for any location or purpose.

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II. Universal Architecture[II] theory

The UA theory proposal considers outputs and findings of a broad research in areas of terrestrial and Space Architecture (see Appendixes I. - III.). One of these findings is related to the definition of Space Architecture (Appendix II.). Respondents were asked how they would define the Space Architecture discipline and a large majority was well aware of the definition introduced by the Team XI (Adams, Bell, Cohen, Sherwood, Hall, Osburg, *et al*.):

"Space Architecture is the theory and practice of designing and building inhabited environments in outer space, responding to the deep human drive to explore and occupy new places. Architecture organizes and integrates the creation and enrichment of the built environment. Designing for space requires specialized knowledge of orbital mechanics, propulsion, weightlessness, hard vacuum, psychology of hermetic environments, and other topics. Space Architecture has complementary relationships with diverse fields such as aerospace engineering, terrestrial architecture, transportation design, medicine, human factors, space science, law, and art…" [11]

Nevertheless, the scope of Space Architecture is meant to cover also specific design on Earth. According to the purpose or function of the architecture related to the space activity, it can be considered as a part of SA discipline: e.g., launch pad, analog stations, simulators, space related research stations[3].

The inclusion of structures on Earth into the SA branch slightly contradicts a provocative note given in the "Mission Statement for Space Architecture" by T. Hall[11] which states that all architecture is Space Architecture and that the Earth architecture is just a subset with whose constraints we are most familiar. This idea is further analyzed and developed by the author and defined in this paper as a Universal Architecture theory. The author's assumption that the SA should but "cannot" include all the terrestrial architecture is found to be a critical linguistic problem more than an architecture classification problem (see Figure 1).

According to the survey performed through an online questionnaire (Appendix II.), to extensive discussions with architects and to personal research, the author found that the current education and outreach in Space Architecture can be improved for more effective development of architecture on Earth, in orbit and on other celestial bodies. Therefore a different term and theory with a different scope and definition is proposed to attempt to strengthen the position of SA and eliminate any discrepancy in linguistics and classification.

This architecture theory concept is called Universal Architecture and its definition currently serves only for the research purposes of this paper. Universal Architecture seeks to unite the fields of terrestrial and space architecture to help understand their relationship and to achieve universal classification (see Figure 2).

Universal Architecture (UA) definition:

Universal Architecture is the theory of building and designing structures and systems as an artificial interface between humans and the surrounding environment: on Earth, in orbit, and on other celestial bodies.

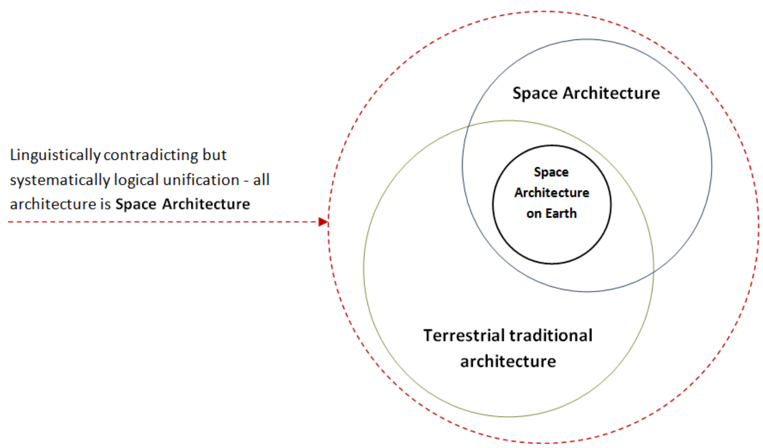

Figure 1. Scheme of relationship between Space Architecture and terrestrial architecture and uniting but contradicting attempt of Space Architecture discipline (red dotted line)

[II] Initially, the term Universal Architecture was considered to be a translation of the name of the Space Architecture discipline into Czech language but during the SA scope analysis the author found that SA is not the entire architecture (as suggested by Dr. Hall). During the research and definition process this term was used as a working term to easily distinguish between the space and terrestrial architecture. The Universal Architecture is now supposed to govern the set of all known architecture sub-fields and also to fulfill the author's goal to unite the space and terrestrial architecture on theoretical level for benefit of both.

III. Universal Architecture classification

UA attempts to unite architecture in space and on Earth based on three groups of classification that could be called human-centric (1.Location, 2.Habitability and 3.Level of gravity). First grouping (A1, A2) is based on location in the universe achievable by humans (Table 1). This grouping is the major uniting principle between the two separated fields of space and terrestrial architecture (Figure 2).

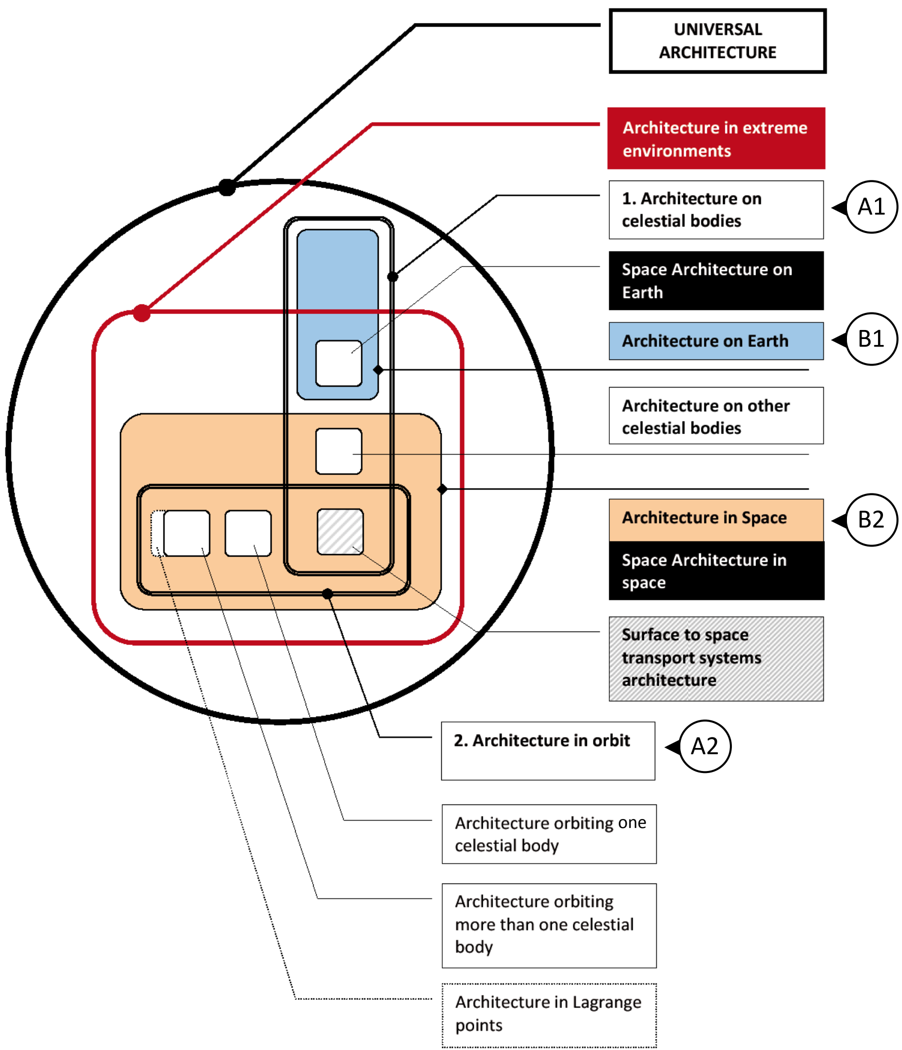

Figure 2. Universal Architecture theory classification and scope

The architecture on celestial bodies differs from architecture in orbit by the properties of the environment it is related to and which are self-preclusive, such as existence of planetary surface, atmosphere vs. orbital position. The secondary, terrestrial-centric (B1, B2) grouping is important for two reasons (Table 1):

- Architects with focus on terrestrial structures may refer to the space industry, research, technologies and architecture outside the Earth's atmosphere, as architecture in space
- Terrestrial architecture is an enormous field compared to architecture in space

Table 1. Location achievable by humans (dual grouping)

A1. Architecture on celestial bodies A2. Architecture in orbit or B1. Architecture on Earth B2. Architecture in Space

A high importance in the UA theory is given to the specific class of architecture called Architecture in Extreme Environments. Extreme environment is an environment in which human can only survive with the support of specific technologies and architecture. If there is no artificial modification to this environment it will be lethal for human. The group of architecture in extreme environment may include architecture on Earth and in space as well but comprehends a much smaller realm of structures compared to UA which is superior to all architecture subclasses. The scope of Architecture in Extreme Environments is also another uniting element in the UA theory (uniting SA and terrestrial architecture) and from the linguistic point of view, the term "extreme" refers to a specific non-standard and non-traditional type of architecture much more clearly than SA. The second grouping according to the habitability of the surrounding environment serves as a closer specification of the Extreme Environment Architecture (Table 2, Figure 2).

Table 2. Level of habitability of the surrounding environment

C1. With natural habitable environments (e.g., regions on Earth) C2. Without natural habitable environments (e.g., Earth's orbit, Martian surface) C3. Uninhabitable environments

A special group is highlighted in the UA theory as the Architecture of Transport Systems (surface to space or space to surface) (Figure 2). This sphere of design crosses boundaries of different locations (Table 1), and environments whose properties change with regard to habitability (Table 2). The suitable classification thus may not just be according to the first two groups, but also with addition of the third group based on the level of gravity (Table 3). Architecture of Transport Systems differs from the other areas by variety and dynamic changes of the external environments and levels of gravity affecting humans during transportation. The proposed classification distinguishes between terrestrial and other gravity levels (Figure 2).

Table 3. Level of Gravity

D1. Terrestrial gravity =1G D2. Artificial gravity xG ($x \neq 0$) D3. Gravity different from 1G (other celestial bodies) D4. Microgravity

The overall system of UA theory is depicted in Figure 2 where the architecture in orbit is additionally categorized in architecture subgroups: architecture orbiting one or more celestial bodies and architecture in Lagrange points.

IV. Universal Architecture Curriculum

The proposed UA curriculum is generally based on UA theory and the educational structure is derived from the UA classification system.

Mission statement:

To teach principles and practice of design in harsh environments and creating sustainable habitable spaces efficiently anywhere where humans can go and live in harmony with the environment.

The particular goal of the Universal Architecture curriculum (Figure 3) is to teach universality of thinking in terms of students' capabilities to design architecture for any environment, focusing on extreme environments and sustainable design. Certain environments or habitable conditions on Earth are not far from those in space in terms of hostility. Application of technologies and principles for current space habitat design in terrestrial architecture may significantly speed up development of technologies for space and may help to enable human space flight.

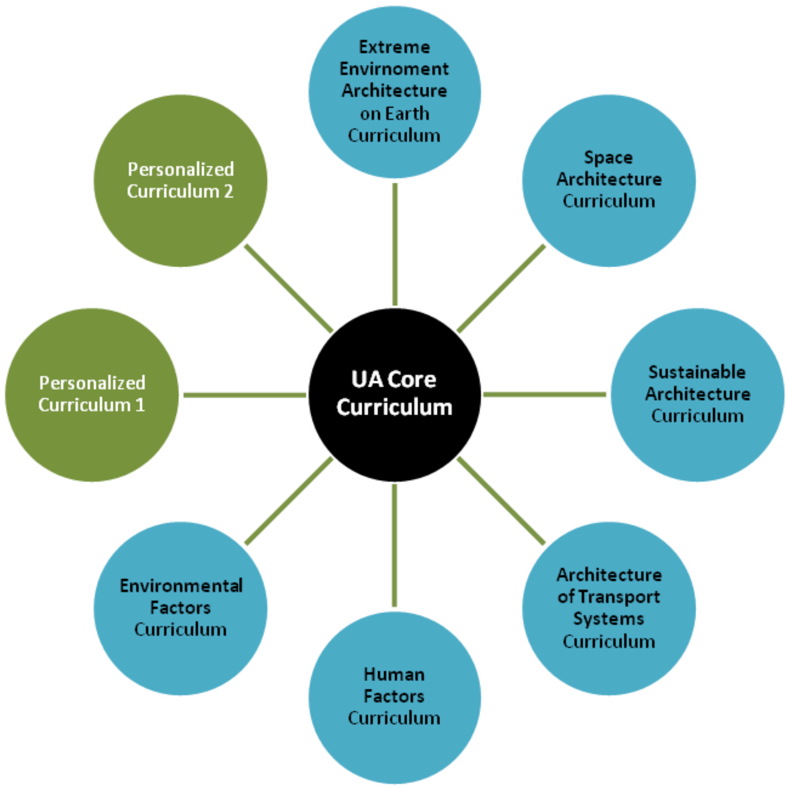

Figure 3. Universal Architecture Core Curriculum (black) includes generic excerpts from each specialized curriculum (blue) and others areas

The alumni of the UA curriculum (Figure 3) would have a unique knowledge of architecture on celestial bodies or in orbit such as:

- Architecture for extreme environments and sustainable design (also with regard to space spin-offs)
- Current space infrastructure utilization in architectural design (urban, building, habitat, station, base etc.)
- Energy efficient designs (also regarding space architecture spin-offs)
- Electromagnetic radiation utilization and shielding (and space spin-offs)
- Development of construction materials and techniques (with regard to space spin-offs)
- Legal framework for sustainable and extreme environments and R & D
- Business and marketing - public and governmental funding and project management

UA alumnus would also acquire unique knowledge of space architecture design for:

- The Moon and Mars
- Structures and habitats on Earth's orbit
- Transport systems (surface to space and space to surface)
- Manned spacecraft for short and long duration space travel
- Analogue and training facilities, etc.

The UA curriculum may also be suitable for personalization (Figure 3). Students who would like to focus on terrestrial applications in their career would do so after a common general introduction into universal architecture, extreme environments and human factors (Figure 4).

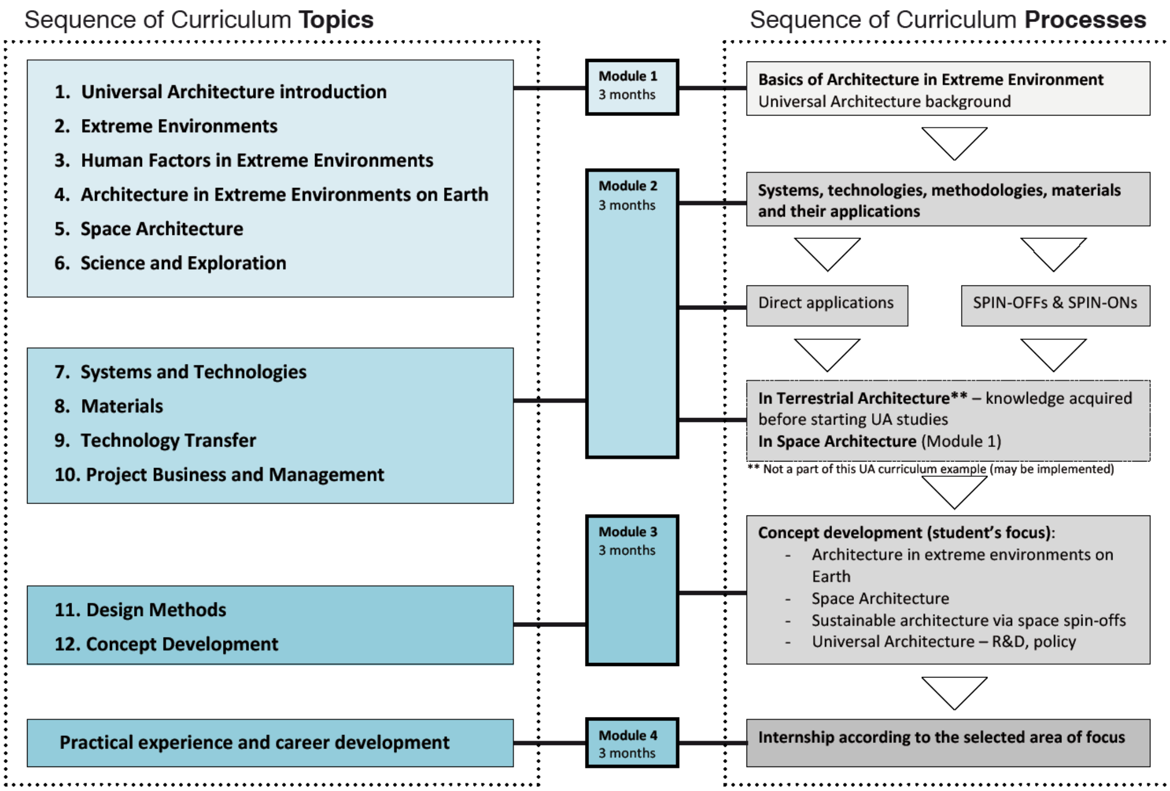

Figure 4. General education framework scheme - example of Universal Architecture Core Curriculum (12 months), (see Appendix IV.)

The UA curriculum faculty would not be composed only of space architects. The traditional architects, managers, scientists, engineers and other experts from a variety of related fields would be involved. Experienced space architects are nevertheless critical for launching a new space architecture educational program. According to the ISU online survey there are 30 space architects worldwide willing to support the new SA program (see Appendix II., Figure 11).

The major potential lies in the student body. Students of architecture are mostly very creative and ambitious people who are taught interdisciplinary work and how to work in teams. Providing a think tank for this sort of group of people might cause a rapid growth within an UA curriculum and furthermore in R&D in space, terrestrial and extreme environment architecture areas worldwide.

A. Universal Architecture curriculum risks and opportunities

1. Opportunities

There is currently only one specialized Space Architecture master curriculum provided in Sasakawa International Center for Space Architecture of the University of Houston. The Universal Architecture curriculum (e.g., under ISU) may have a much broader scope and alumni of this program would have a much larger field of possible applications (job opportunities) in front of them, since the philosophy of these studies is to connect terrestrial architecture with space architecture, providing the space architecture background. UA studies would be strongly focused on application and much less on conceptual studies for distant future space flights (the scope may be flexibly adjusted according to the industry demand).

There is currently no education like the Universal Architecture curriculum. This unique curriculum proposes to connect the knowledge of space and terrestrial architecture for the benefit of development in both areas. The logical conclusion from current trends in terrestrial architecture design, like “green energy design”, “environmentally friendly design” and self-sustainable design with regard to the global notion of humankind’s current “un-sustainable” way of living is that the UA program may be in very high demand. Hundreds of architecture universities around the world may be interested to cooperate.

2. Risks

The risk surely lies in the right initiation and conduct of the program. Also gaining worldwide understanding is important since if this is not acquired then UA might suffer from a lack of students. There is also a certain risk in implementation of the program, particularly the second set of three months (Figure 4) focusing on the technology and methodology transfer from space to Earth and back. This area seems to be the least explored in terms of education. Nevertheless experts at ISU and collaborative space architects and architects worldwide might well help to develop this part of the curriculum and mitigate risks in its initiation.

There is a risk that the UA theory will not be accepted in the space architecture or architecture community. The reason for this could be a major flaw found in the UA theory and curriculum, general fear of accepting new ideas or simply a prejudice. To mitigate this risk, the start of the curriculum would need to be supported by a university that is well established and respected in the world.

3. Rewards

Universal Architecture education may raise a large interest in the space sphere and might initiate a strong movement of utilization of space technologies, thanks to the strategic capabilities of UA alumni.

Author’s hypothesis is that the impact on society would be mostly in increased space outreach, in more sustainable ways of living on Earth and positive notions about the space sphere. UA would also help faster development in the area of human space flight. Very probably there would also be an increase in the number of private companies with a particular interest in space tourism since there would be many more creative individuals and many more ideas about what to do in space and how to settle there. The space sphere would thus be better promoted and better appreciated.

B. University affiliation – selection criteria

The implementation of the new curriculum will depend on many factors most importantly on affiliated university or universities. ISU’s philosophy of three Is (International, Interdisciplinary and Intercultural) is considered as a main component of the affiliation strategy.

Generally, the affiliation of the UA program may be perceived from a bilateral or multilateral collaboration point of view (with academia, research institutes, industry etc.). For the bilateral agreement the requirements on the chosen university’s departments and facilities will be very high as well as requirements on the experience with SA and the proximity of the aerospace industry. In the case of multilateral cooperation, the UA curriculum will have plenty of options for fulfilling its very high requirements on university facilities and educational personnel and tools.

Initially, six requirements are chosen to be the basic drivers for the potential affiliation of UA studies. These are divided into two groups with high priority (I.) and low priority (II.). Every affiliated university would thus have to pass high priority requirements to be able to participate in the UA curriculum. Passing also low priority requirements would mean invitation for the university to the multilateral UA educational program.

1. *Priority I. – requirements (ISU driven)[III]:*
   A. Architecture department - Extreme Environment Architecture, UA or SA studies require architecture department at the university which is open to interdisciplinary and international collaboration.

   B. Architecture degree granting program (doctorate)
      a. ISU is considered by the author to be the founding body for these new space architecture studies. ISU currently does not provide doctoral studies program and its establishment is considered to be an important step in development of all ISU study programs.
      b. The educational program should be able to accommodate students who have completed Masters Studies in architecture who are interested in doctoral studies and research. Masters education in architecture is considered by the space architecture community to be a requirement for space architecture studies.
      c. University should enable high level research.

   C. Access to aerospace engineering department or similar in the vicinity - Aerospace engineering is an essential part of Universal Architecture studies that combine many subjects essential for SA education and not usually taught at traditional architecture universities.

   D. Access to human factors and ergonomics department or similar in the vicinity - Human factors are more relevant in the extreme environment architecture than in traditional architecture. Design for life threatening environments requires much closer study of human body physiology, human psychology and other related aspects of human existence.

2. *Priority II.– requirements:*
   E. Experience with Space Architecture programs or past collaboration
   F. Proximity to aerospace industry

According to the online survey on SA, the highest number of responses comes from the USA (see Appendix II., Figure 6). Therefore it may be a logical step to initiate this type of educational activity in the USA. As an example of university selection for bilateral agreement a preliminary online research was performed on USA universities[IV]. Only four institutions would fulfill all requirements of I. and II. Priority: Georgia Tech, MIT, University of Michigan and University of Southern California. To have more collaborative options, it may be considered to apply the above selection criteria with certain margins.

C. Universal Architecture Curriculum example (Figure 2, Figure 3, Figure 4)

This proposal is based on D. Duerk Aerospace Architecture Curriculum, SICSA[V] lectures, and ISU faculty requirements. It represents the core of UA curriculum and UA theory and would serve as a base for the other curricula (Figure 3). This brief curriculum summary is not supposed to be a comprehensive list of UA subjects. It is a conceptual idea of an educational structure (see Appendix IV).

[III] The criteria are mostly based on requirements of affiliation to ISU which does not dispose of architecture department or doctoral granting program
[IV] Data about US Universities gathered and kindly provided by Dr. Mark Cohen
[V] Sasakawa International Center for Space Architecture

V. Conclusions

Integrating a Space Architecture curriculum into broader Universal Architecture studies is proposed in this paper. This integration may bring a number of benefits:

- Many issues of terrestrial architecture could be addressed via the SA approach and vice versa.

- Space Architecture education based on dynamic system of market needs with particular emphasis on personal career development may be a logical step in SA education regarding current difficulties (budgetary constraints) in the realization of SA.

- Addressing sustainable development, environmental challenges and technological progress via space technology spin offs may help terrestrial architecture to find the key solutions to global issues but also provide a technology development base for space architecture.

- Joining SA with terrestrial Extreme Environment Architecture under the UA theory may help inform about SA and popularize currently the almost unknown field of SA in the public domain.

- UA theory is a generic platform for the development of architecture anywhere where humans can go based on generic design principles of human needs and environmental constraints. UA teaches respect to any environment.

- The UA curriculum enables personalized curricula in areas of sustainable design, transport systems design, space architecture, human factors, environmental factors, their combinations and others based on the Universities' affiliation. The UA curriculum is thus not solely focused on educating architects.

- The UA curriculum promotes international, interdisciplinary and intercultural education (as practiced at ISU)

- SA is an emerging small field, very strong in terms of people and with great potential in the future but currently very weak in areas of funding, business, job opportunities and also in possibilities to obtain space architecture education.

- SA is a very young discipline which is estimated to be in high demand in twenty years. Linking space architecture to the current economically strong sustainable terrestrial architecture market (see Appendix III.) may bring many benefits to both fields and especially help to employ space architects.

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Appendix I.

Workforce in EU space sector

Research in the area of Space Architecture education was motivated by a number of factors (personal high interest in Space Architecture, search for an application for space architects and job opportunities) but mostly by research performed at ISU which focused on the requirements of the space workforce demand.

The space sector in the EU is lacking a workforce with a specific set of soft and hard skills. Generally, the hard skills are much easier to quantify than the soft skills and the highest hard skills demand was identified in the area of combined engineering and management skills. The soft skills depend mostly on social and personal intelligence and are much harder to measure. Nevertheless, the ISU research pointed out soft skills which are in high demand by a number of space institutions and companies[2]:

- Analytical and conceptual thinking
- Communication (also interdisciplinary)
- Creativity
- Motivation
- Teamwork (see Figure 5)

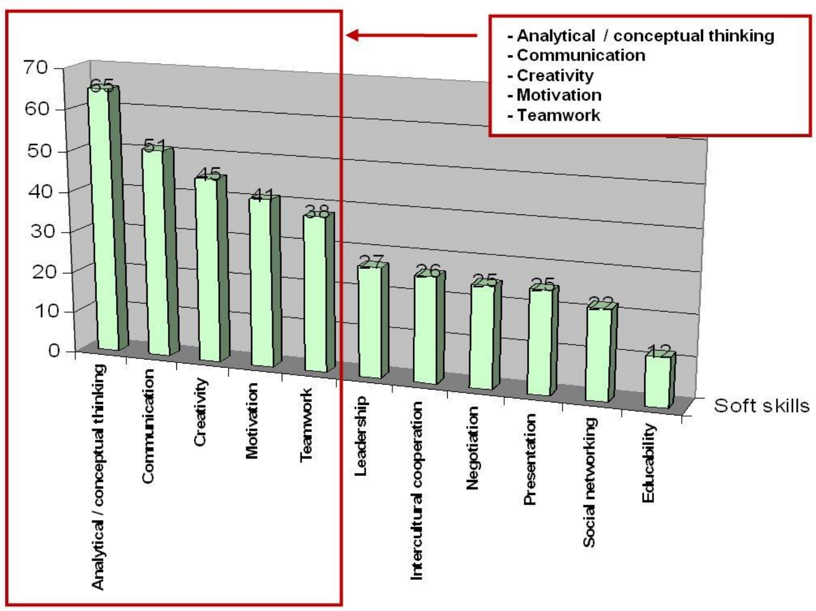

Figure 5. Ranking of soft skills in function of frequency mentioned[2]

This research did not provide an option for (space) architecture hard skills but the soft skills in the highest demand identified are (or should be) inherent to architecture profession.

Architects need to have skills to conceptualize and to see the big picture; they are well balanced professionals with good analytical and communication skills. Communication, as in delegating to key individuals, interviewing and negotiating is the architect's essential role during the project development while directing the design along the project path. Facilitating communication in the team of professionals and maintaining self and team motivation are important for efficient teamwork and meeting the required milestones.

Creativity is a fundamental skill of the architect who provides a "tangible" solution to its client based on a number of inputs and environmental requirements. The architect's capability to be creative and his/her "level" of creativity makes him a unique and wanted individual who can hardly be substituted in the process of the project creation.

The research on the demand for generic soft skills in the space sector provides an arena for speculation e.g., what is the value of soft skills compared to hard skills and whether the space architects are or are not in high demand. To explore a few areas of the space architecture discipline, specifically the state-of-art of SA workforce, the online survey was launched at ISU by addressing a worldwide space architecture community. The focus of this research was also on education and employment opportunities in the SA field.

Appendix II.

Questionnaire on Space Architecture

In order to understand current climate in the space architecture field (particularly the workforce) an online questionnaire was launched via ISU internet website. In this survey only professionals, active in the space architecture field (space architects) were addressed. The database of space architects was created by author, based on meta-research and ISU contacts database. This database of space architects now contains 92 practicing space architects in total all around the world.

The questionnaire was successfully sent to 79 space architects during the period April – July in the year 2009. Thirty six respondents filled and submitted the questionnaire which meant 45% return. The strategy behind the success of such a high return lies partially in the personalized distribution of questionnaires, and partially in the high interest of space architects who were willing to participate. The ISU alumni network contributed to this survey by 41% of respondents.

The geographical distribution of responses is depicted in Figure 6. The USA clearly dominates and we can assume that this large interest may be influenced by the US human space flight program and the only Space Architecture program, the Sasakawa International Center for Space Architecture (SICSA) in Houston.

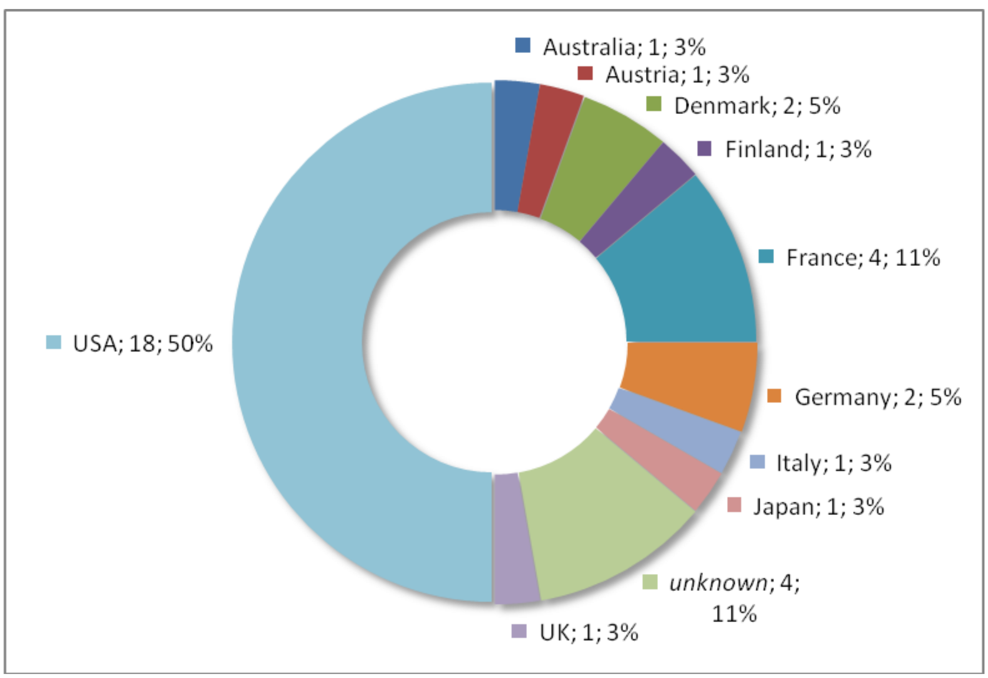

Figure 6. Approximate geographical distribution of questionnaire respondents (location; number of responses; %), (Source: ISU)

The background of respondents was important for understanding the education of space architects (see Figure 7). Most of the respondents have a background in engineering and architecture. The Space Architecture background has only 13 % of respondents. Large majority of respondents (86%) consider acquiring education in traditional terrestrial architecture as an essential pre-requisite for studying and understanding the field of Space Architecture.

The current space architects' scope of work (or focus) was addressed in the next question. Most of the respondents (52%) are currently working in area of "Human Factors Design for Space Architecture", while 38% is focused on "Architecture on Celestial Bodies (Moon, Mars)". These numbers are identical with areas of Space Architecture in the expected future demand by year 2030 (Figure 8). Currently minimal importance is given to areas such as: business, management, policy and law in space architecture.

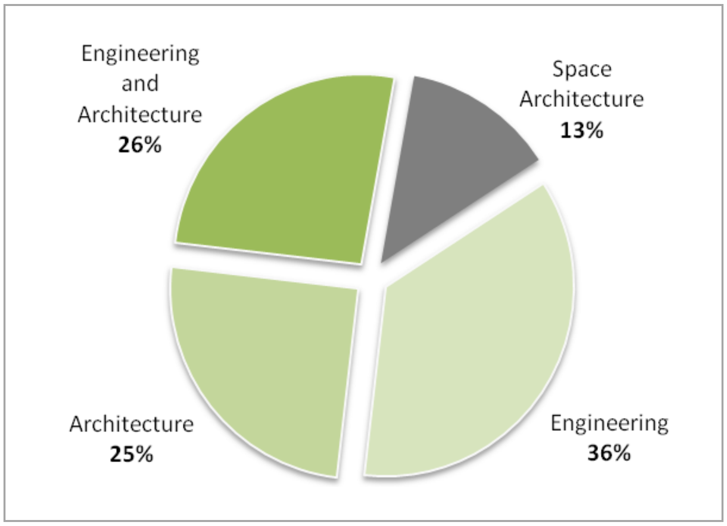

Figure 7. Background of respondents

The majority of space architects (44%) work in SA just part time. Only 16% of respondents have the field of Space Architecture as their fulltime employment, and for the rest (40%) SA is an unpaid field of interest (Figure 9).

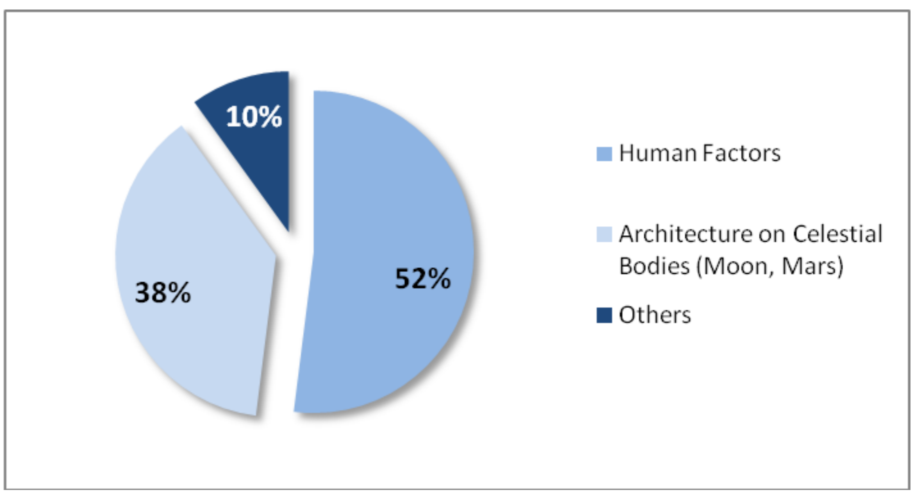

Figure 8. Respondents' area of focus and also focus demand

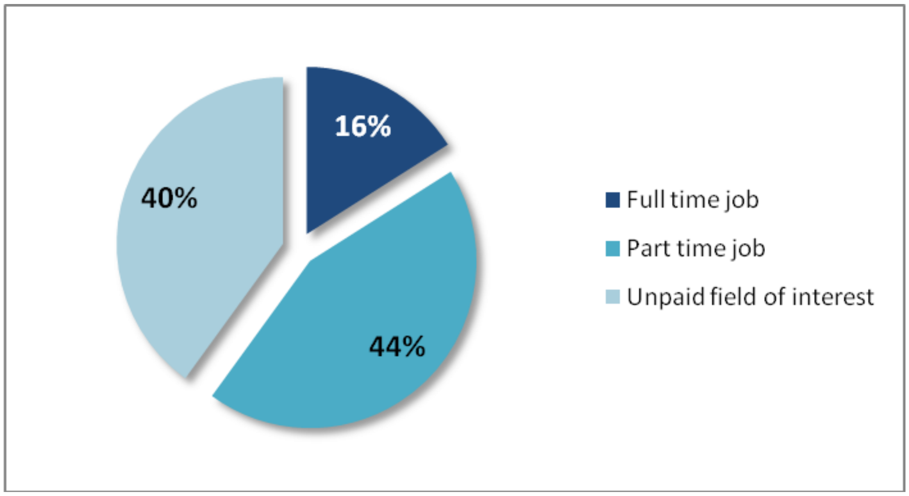

Figure 9. Professional involvement of respondents in the field of Space Architecture

The current demand for space architecture profession is perceived by the majority (58 %) of space architects as increasing. The rest (42%) of respondents do not regard the current demand as increasing, predominantly due to budgetary cuts or financial constraints which are mostly related to the human spaceflight space agencies' plans (Figure 10).

Nevertheless, there is a prevailing opinion by the majority of space architects (94%) that there will be an increase in demand for space architects by the year 2030 (see Figure 10).

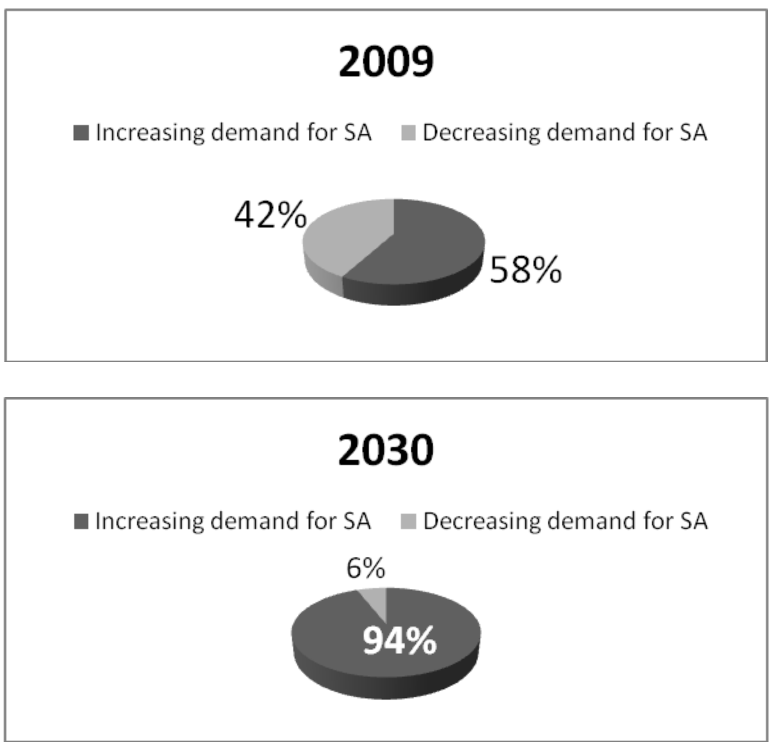

Figure 10. Demand for the space architecture profession now (2009) and estimate for the future (2030)

The final question in the online survey addressed the personal interest in cooperation on Space Architecture educational program with ISU. 83% of respondents would be willing to cooperate on SA module with ISU (Figure 11) and 30% would be available anytime.

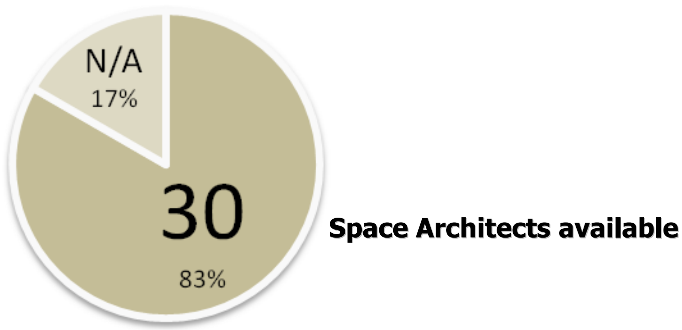

Figure 11. Number of respondents interested in cooperation with ISU on new educational Space Architecture program in 2009

Preliminary conclusions from the data obtained by the online questionnaire on Space Architecture are that SA is an emerging small field, very strong in terms of people, with great potential for the future but currently very weak in areas of funding, business, job opportunities and also in possibilities to obtain space architecture education.

During the joint research in both terrestrial and space architecture field, the author finds a great potential in linking the "young and weak" Space Architecture discipline, (dealing with a much broader scope of environments) to the traditional and "powerful" terrestrial architecture discipline. This connection may help in education, research, development and practicing the space architecture profession. The need for a space architecture "business plan" behind its mission statement was also identified by the author.

This "business plan" may be called Universal Architecture theory which is proposed to enable the faster development of architecture in space. Architectural theory is usually not used in the practical design process. Architects design intuitively. However, architectural theory is used during the education process [13]. Interconnecting the Space Architecture and terrestrial architecture discipline is thus found as a key to space architecture education and it is based on a similar philosophy which was touched by space architect Theodor Hall in the Mission Statement for Space Architecture:

"All architecture is Space Architecture. Earth architecture is just the subset with whose constraints we are most familiar." [11]

Appendix III.

Trends in terrestrial architecture: Sustainable and extreme environment architecture

A. Sustainability Trends

"Shell estimates that after 2015, supplies of easy-to-access oil and gas will no longer keep up with demand…" says Shell Oil CEO Jeroen van der Veer[9]. The oil market is now unpredictable. *"In 2007-2008, rapidly rising oil prices helped trigger a deep world recession"* and in the near future oil market may be responsible for even worse global economic situation[9].

Increasing global need for energy is a new challenge for the traditional architecture discipline. The prospects of the International Energy Agency point out increasing requirements for infrastructure and energy supply (Figure 12). Current consumption of cities is about 48 %[7], (Figure 14**)** of the world's energy and current growth of cities is 2 % per year. It is estimated that 60 percent of the global population (about 5 billions) will live in cities by 2030[10].

Sustainable or green architecture thus becomes an important topic of the 21st century. Another area addressing the same issue is pollution of the local environment, lack of fresh water, negative irreversible changes of the living environment etc.[14]

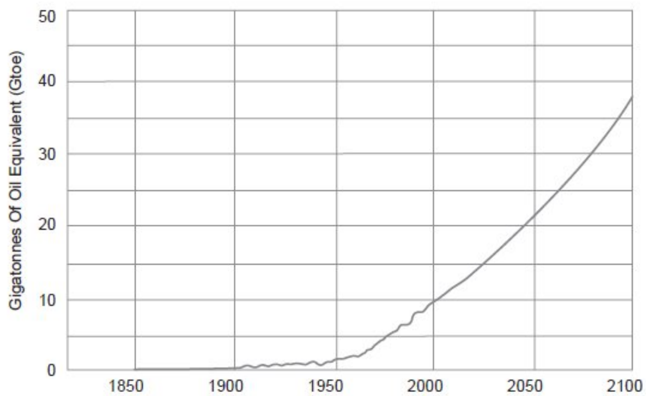

Figure 12. Prediction of global energy consumption[14]

More interestingly, sustainable architecture (Figure 13) is not only a necessity but also a good business: *"In fact, green building market has grown in spite of the market downturn. …we expect green building will continue to grow over the next five years despite negative market conditions to be a $96-$140 billion market"*[8]. The U.S. Green Building Council had even more optimistic predictions when it stated in April 2009 that it expected the green building market to more than double in size[5].

Figure 13. World's First LEED Platinum Data Center Opens in Germany (230,000-sq.ft.). - The efficient use of energy and resource-conserving design have made it the first data center in the world to achieve LEED Platinum[12]

Innovative technologies in space architecture may be one of the sources for sustainable, green architecture on Earth (Figure 13). The confined, autonomous habitat designs and architectural principles for space may be utilized in many terrestrial applications responding to current needs. Closed loop life support, water recycling or power system derivates may be the answers to many energy or environmental issues worldwide (Figure 14).

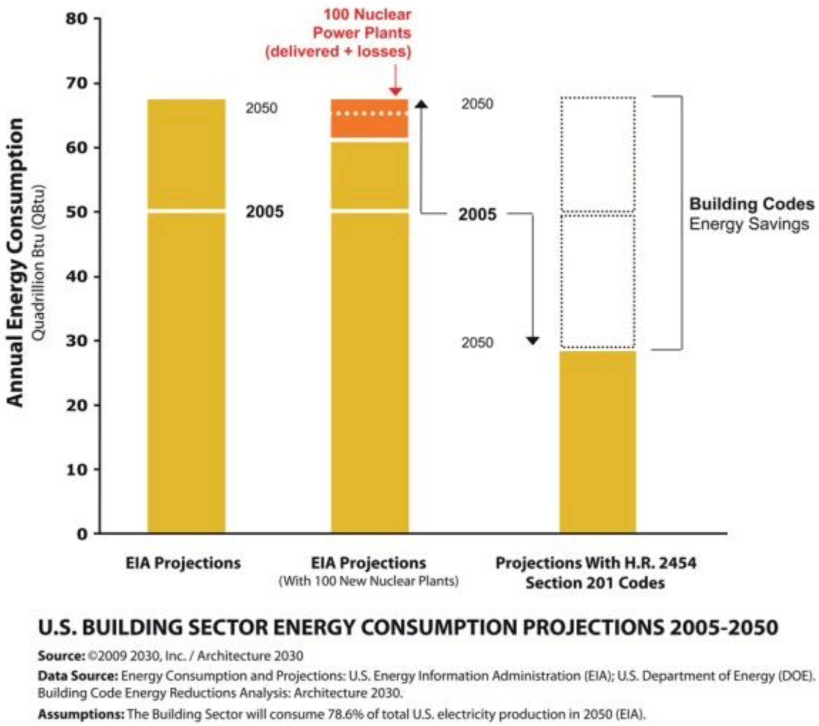

Figure 14. Energy savings by architectural design[7]

B. Extreme environment architecture on Earth

Extreme environment architecture on Earth is related to environments where the psychological adaptation or technological innovation has to be implemented in order to survive e.g., habitats in polar regions, mountains, deserts, underwater, on water, but also living in areas devastated by natural disasters[6].

The Belgian polar station (constructed in 2007) is an excellent example of self-sustainable architecture in an extreme environment using also technologies and methods of design derived from the space industry (Figure 15). This Antarctic base is an entirely self-supporting habitat taking into account local climate conditions and using renewable energy resources[1].

Figure 15. Belgian fully self-sustainable Antarctic research station

Similarly, the new Antarctic European research station Concordia realized in cooperation between France and Italy (2005) is environmentally friendly (Figure 16). It is the first terrestrial architecture, testing water treatment systems (black water) originally designed for application in space under supervision of European Space Agency[4].

Figure 16. Concordia station in Antarctica using ESA water treatment systems

There is no doubt that similar space derived methods and technologies for self-sufficient architecture could be applicable in other extreme environments on Earth. Specifically, the water treatment systems may help anywhere the lack of potable and fresh water is an imperative need.

Appendix IV.

Universal Architecture Curriculum example

1. ***Universal Architecture – [extra] terrestrial introduction***
   In this theoretical introduction the UA system is explained as a holistic architectural theory helping in practical application of architecture.
   - **Theory**
     - Architecture as an interface between humans and the environment on Earth, in space and everywhere where humans can go
     - Architecture as a holistic design approach
   - **Practice**
     - Scope of extreme architecture application possibilities and career prioritization

2. ***Extreme Environments***
   By mastering architecture in extreme environment the architect can better develop and master also the field of non-extreme terrestrial architecture.
   - **Human Safety**
     - Introduction to human factors in extreme environment
   - **Natural Extreme Environments on Earth and in space**
     - Temperature, humidity, wet environments
     - Isolation, confinement, remote sites
     - Atmosphere and vacuum
     - Gravity
     - Radiation - on Earth and in space
   - **Artificial Extreme Environments on Earth and in Space**
     - Training and experimental facilities (analogues and simulators)

3. ***Human Factors in Extreme Environment***
   Architecture involves humans as a major factor and driver of the design therefore their safety and comfort have to be secured.
   - **Physiology risks and countermeasures**
     - Temperature

- Humidity – wet and dry
- Hyperbaric, low pressure, artificial atmosphere environments
- Industrial stressors - acoustic noise, vibrations
- Causes of SMS
- Effects of aviation
- Effects of microgravity, reduced gravity and hyper gravity
- Effects of radiation
- Human kinetics and anthropometry

- Psychology and human performance
- Confinement and isolation
- Circadian rhythms, fatigue
- Cognitive and physical performance in adverse environments
- Survival, reaction to failures, critical situations, disasters
- Critical decision making
- Crew selection, CRM, team organization and management
- Effects of microgravity, reduced gravity and hyper gravity
- Armed conflicts

4. ***Architecture in Extreme Environments (AEE) on Earth***

In the UA curriculum the essential part and the joining element of architecture on Earth and in space is Architecture in Extreme Environment on Earth.

- **Regional architecture, habitats in polar regions, mountains and deserts**
- **Disaster management architecture**
    - Rescue habitats
    - Transportable, deployable, convertible habitats
- **Solutions for urban sprawl, industrial pollution, overpopulated area**
    - Water recycling systems
    - Power generation systems
    - Infrastructure establishment
- **Sustainable and zero energy architecture**
- **Off shore platforms**
    - Oil and gas rigs
    - Escape platforms
- **Underwater habitats**
- **Extreme environment architecture for tourism**

5. ***Space Architecture (includes AEE in space)***

Placing Space Architecture in the broad context of Extreme Environment habitats is a core idea of the UA program. This part of the UA curriculum would be based on the SA definition and supported by the worldwide SA community.

- **Space Architecture on Earth**
    - Analogs, simulators, training facilities
    - Ground segment infrastructure
- **Space Transportation**
    - Launch vehicles
    - Spacecraft design for human spaceflight
    - HMI design
    - Various G load design
- **Space Architecture on other celestial bodies**
    - Classification
    - Planetary urbanism – settlement strategy
    - ISRU techniques and local architecture style
    - Major drivers for planetary architecture development
- **Space Architecture on orbit**
    - Orbital mechanics

- Short and long duration space habitats
    - Space stations
- **Space Architecture for virtual worlds**
    - Promotion, outreach and consultancy services

6. ***Science and Exploration***

This part of the UA studies will explain and strengthen the reasons for human presence in extreme environments within the historical and scientific context. Students should know the solar system in terms of the relationships between the objects in the solar system and the types of planets.

- **Basics of astronomy**
    - Habitable zones - Galactic, Circumstellar, Non-Circumstellar etc.
    - Milky Way
    - Solar System
- **Orbital mechanics**
    - Orbits and perturbations
    - Transfer techniques
    - Trajectory design
- **Space weather**
    - Impact on processes on Earth
    - Impacts on interplanetary flights
- **Earth and space exploration**
    - Exploration history on Earth
    - Space exploration history
    - Human spaceflight history
    - Space Architecture and mission design history
- **Current human exploration on Earth**
- **Programs of space agencies**
- **Private endeavors and enterprises**

7. ***Systems and Technologies***

Engineering development, system design and technologies on the shelf and innovative development trends are at the core of all architecture realization. Keeping in touch with current and relevant technical trends is an important task of this UA program part.

- **Structural types and construction methods**
    - Rigid, foldable, crushable and deployable structure
    - Inflatable structure
    - Modular systems
    - Airlocks, dust locks systems
- **Power systems**
    - Based on self-sustainable energy generation
    - Non-regenerative systems
- **Environmental control and life support systems**
    - Closed, open, (bio) regenerative loop systems principles
    - Water, food, atmosphere, waste treatment systems
- **Transport systems, mobility**
    - Selection of the transport strategy (EDL, deployment)
    - Construction and supply chain logistics
    - Exploration and research
    - Tourism
    - Manned vs. robotic transport
- **Communication with sites in extreme environment**
    - Remote sites infrastructure
    - Current infrastructure utilization
    - Telecom satellite infrastructure
- **EVA, suits and protective garment for extreme environment**

8. *Materials*

Available advanced materials make the Architecture in Extreme Environment possible. The development in the material sciences is enabling humans' presence in the harshest environments on Earth and in the universe.

- **Materials requirements for extreme environments**
  - Flight-proven materials
  - Metal alloys
  - Composite materials
- **Protection against harsh environments on Earth and in space**
  - Radiation shielding /space, Earth/
  - Materials for pressurized structures
  - Impact shielding /space-micrometeorites, Earth-climate/
  - In situ materials
- **Advanced materials and development**
  - Nano-materials
  - Smart materials

9. *Technology Transfer*

The utilization of technologies developed for space application on Earth and vice versa and knowing the process of the technology transfer could improve communication and increase growth of all Extreme Environment Architecture disciplines.

- **Space spin offs for terrestrial architecture application**
- **Terrestrial spin offs for space architecture**
- **Technology transfer management**
  - Legal aspects, intellectual property
  - Business aspects
  - Research and development enhancement

10. *Project Management, Business and Policy*

Every project has to be financially viable and needs specific organization and team structure.

- **Project organization and coordination**
  - Methods of organization and team selection
  - Software applications
- **Project economics**
  - Project strategy
  - Marketing
- **Project financing**
  - Governmental and private research support
  - Private, commercial endeavors
- **Law, policy and politics in extreme environments**
  - Earth
  - Space
- **Research and development**
  - Military
  - Civil

11. *Design Methods*

To search out, read, and understand the validity of research reports as well as be able to conduct small-scale primary research on their own using the basic scientific method, ethnographic methods, online and software tools.

- **Applying the design theories**
  - Universal Meta-theories
  - Thematic / Analytic theories
  - Theories of synthesis
  - How to create design theory

- **Applying the design methods and software**
    - CAD and Parametric design
    - Concurrent design
    - Digital prototyping

- **Communication**
    - Project Management
        - Project and team organization
        - Teamwork - Intercultural, Interdisciplinary work and communication
    - Project presentation
        - Writing a report, article, conference paper, designing poster
        - Digital and physical modeling techniques
        - Web based presentations

12. ***Concept Development***

Correct application of a design theory and a design method is a base for good results in the design process. The complex architectural design includes many areas that need to be balanced according to the initial project objectives and other aspects of the project.

- **Mission, project strategy**
    - Project objectives
    - Mission goals and definition
    - Financial and legal constraints
    - International cooperation benefits and constraints
    - Potentials for development and conversion
- **Mission operations**
    - Understanding of differences between mission strategy and mission operations and the impact that operations have on the systems that implement the purpose of the mission.
    - Primary and secondary operations the architecture has to support
    - Backup scenarios and emergency situations
- **Extreme environment [Site conditions]**
    - Assessment methods and priority for human safety
    - Classification and synthesis of environmental issues critical for design - Design drivers of a site with, without atmosphere or an un-breathable one, extreme temperatures, high radiation exposure, as well as understanding such issues as local topography and climate.
    - Optimal site layout regarding project objectives and the environment
- **Human Safety**

  Mission objectives, operations and properties of extreme environments are related to human safety.
    - Risks associated with overall mission, project scenario and proposed mitigation techniques
        - Loss of atmosphere, ECLSS failure
        - Structural failure, fire emergency
        - Energy and items supply backup
        - Logistics backups
- **Anthropometry**

  Dimensions and motion envelopes of the human body in the specific gravity conditions are essentials for an understanding of extraterrestrial or extreme environment spatial requirements.
    - Confined environment design and HMI design
    - Space suit – human interaction and comparative motion analysis
    - Ports, airlocks, dust-lock, suit-lock, suit-port
- **Habitability**

  Impacts of environmental stressors and the associated habitability and applications at a level of detail that includes human factors on interior spaces design.
    - Human/human interaction – communication, team culture, etc.
    - Human/technology interaction – HMI, software, automation, robotics, perceptual, etc.

- Human/environment interaction - color and décor, illumination, spaciousness, individual control, variety, and the ergonomics

− **Systems integration**

Use the tools of systems analysis to more deeply understand their projects and critically analyze them for quality; integrate the wide variety of concerns from safety, habitability, and structure, to aesthetics into the design of facilities of architecture for extreme environments.