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Space Architecture and Habitability: An Asset in Aerospace Engineering and Architectural Curricula

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Abstract. Space Architecture is interdisciplinary; it connects diverse fields such as aerospace engineering, architecture and design, human factors design, space sciences, medicine, psychology, and art. Space Architecture combines the accuracy of technical systems, human needs for working and living, the interface design for the relationship between humans, and the built and natural environments. It is simultaneously technical, humanistic, and artistic and deals – most importantly - with the design process from a "big picture" perspective down to every detail of each component. In addition to traditional knowledge of planning and building processes, special knowledge is needed regarding how to design for humans in extreme environments and how to do so creatively. Many universities around the world offer aerospace engineering undergraduate and graduate programs, but only a few relate to the field of Space Architecture. This paper presents examples of educational practices illustrated with student projects from European and US academic institutions that offer space architecture as a mainstream or major component in their curriculum. It further explores the necessity of incorporating the discipline of Space Architecture and Habitability into aerospace engineering and architectural curricula [16].

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1 Introduction and Historical Precedents

Space Architecture, as a discipline, is not new. When NASA and the former Soviet Union turned their views towards long-term human missions in the 70s, space architects and designers were involved.

In 1967, architect Maynard Dalton was among eight people from the 'Advanced Spacecraft Technology Division' who received an award for "Preliminary Technical Data for Earth Orbit in Space Stations" [2]. In 1968, Dalton and Raymond Loewy, a world-renowned industrial designer, worked on the Saturn-Apollo and Skylab projects. Loewy is well known for his improvements to the existing layout, such as the implementation of a wardroom, where the crew could eat and work together, the wardroom window, the dining table, and the color design among other additions [8]. Dalton prepared the Skylab Experience Bulletins and became project engineer for the Space Station module (1971). At about the same time, from 1965 to the 1980's the Soviet Union's space systems 'Barmin Design Bureau' produced a complex research and planning project designing structures and mobile systems for a long-term lunar base. Architectural and structural design aspects were recognized as key elements of the project and thoroughly defined. The Lunar base 'Zvezda' was part of that work (1960-1980).

Galina Andrejewna Balaschowa can be considered the first female space architect. She started working at the Experimental Office OKB-1 as an architect in 1957 and moved a few years later to a space architecture department, where she worked closely with the founder of the Soviet space program Sergei Pavlovich Korolev. She contributed to the design of the Sojuz spacecraft, and Salyut and Mir stations.

Until today, many designs of space habitats have been created, but only a few were implemented in space programs around the world. Currently, only the International Space Station and Chinese Space Station are orbiting the Earth.

Both space stations are grand achievements, from an engineering and scientific point of view. However, important human factors and habitability design components seem to be sacrificed first, mainly because of budget cutoffs. As a result, the 'Habitation Module' for the ISS was suspended during the construction phase and only since 2008, all six crewmembers are provided with a personal sleep compartment.

In 2002 several members (including the authors) of the Technical Aerospace Architecture Committee of the American Institute of Aeronautics and Astronautics (AIAA) organized the first Space Architecture Symposium during the 'World Space Congress' in Houston in 2002. There, the following mission statement was developed: *"Space Architecture is the theory and practice of designing and building inhabited environments in outer space"* [3].

Following this quotation, Space Architecture as a discipline comprises the design of living and working environments in space and on planetary bodies, such as the Moon and Mars, and other celestial bodies. This includes space vehicles and space stations, planetary habitats, and associated infrastructure. Earth analogs for space applications, simulation and test facilities belong to the extended field of Space Architecture. Earth analogs include Antarctic, airborne, desert, high altitude, underground, and undersea environments;, as well as closed ecological systems.

2 Space Exploration Goals and Challenges

In contrast to early space missions, spacecraft design concepts for future space exploration cannot be based mainly upon engineering and structural requirements [6]. Humans in future long-duration spaceflight and exploration endeavors will play key roles within the mission. Consequently, human needs and requirements must be addressed in overall mission architecture and spacecraft design. Human factors need to be taken into account at every stage of the design process — considering people to be more than an 'element' of the system but its modifier and innovator.

Planning and building future long-term space missions will challenge both technology and human endurance. According to several space agencies including ESA, current road maps with planetary exploration missions' scenarios include short expeditions to the Moon, cis-lunar locations, asteroids, and long-term manned missions to Mars.

A human mission to Mars will include long travel times (6-9 months) each direction and a stay on the planet's surface between 3 months to 2 years [1, 22, 24]. It is obvious that all mission aspects influence each other and have to be addressed beforehand - at planning and design phases. Especially design considerations related to missions' lengths and destinations change significantly [16]:

- The longer and more isolated the mission, the more important will be the qualitative design of the habitat, including layout and integration of its structures, systems, and utilities.
- The longer and farther away from Earth, the more sustainable the habitat has to be and the more facilities will be needed for personalized activities, etc.

In order to meet challenges associated with space exploration, a new generation of professionals has to be educated [5]. Today's students and future spacecraft designers need to be prepared for the planning of human missions and designing appropriate artifacts. It is important that future mission planners, engineers and architects, as well as other professionals involved in the design for manned spaceflight are educated in order to [16]:

- Learn about space systems and human factors as equal elements of a spacecraft and mission design;
- Understanding connectivity and relationships between all design elements and overall mission planning;
- Operate at all scales from the 'overall picture' down to smallest details;
- Provide directed intention and judgment – not just analysis – towards design opportunities;

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- Address relationships between human behavior and built environment;
- Interact successfully with diverse fields and disciplines throughout the project's lifecycle.
- And last but not least: critical thinking.

Current problems of academic training for example include lack of understanding requirements derived from expertise in human factors that students and professionals trained in space engineering frequently demonstrate. On the other hand, students and professionals in the fields of architecture and design often are not adequately prepared with respect to engineering requirements and evaluation criteria. In addition, interdisciplinary interaction is challenged by dissimilar research and working methods, different glossary used for identification of design problems and requirements, and evaluation criteria that are often inconsistent. All those factors make teamwork and planning for future manned space missions even more difficult.

3 Habitability Principles

Knowledge of basic design requirements for a human mission is required already at an early stage of the design process. Several key requirements for human missions drive habitation design, examples include:

- Life Support (Atmosphere; Thermal Environment and Humidity; Food; Hygiene and Waste Collection; etc.)
- Hazards (Micrometeoroids; Microgravity; Radiation; Safety Hazards; etc.)
- Behavioral Implications (Personal Space and Privacy; Social Interaction versus Isolation; etc.)

Although various definitions for the term 'habitability' exist, it can be understood as *"a general term that connotes a level of environmental acceptability"* [10] as stated by Connors, Harrison, Akins and Faren in their book 'Living Aloft – Human Requirements for Extended spaceflight. Habitability can be used as a *"a general term to describe the suitability and value of a built habitat (house or spacecraft) for its inhabitants in a specific environment (Earth or Space) and over a certain period of time. Set into the space context, habitability can be understood as the measure of how well the (built) environment supports human health, safety and well-being to enable productive and reliable mission operation and success"* [15].

Historically it has been considered a low priority in the space mission planning process. Architects and engineers still discuss the degree of its importance, but when the effects of impaired habitability are understood as critical [7] and potentially life threatening, then understanding habitability and Human Factors *"will make mission success more likely"* [21].

Another definition refers to the Habitation Readiness Levels (HRLs) described by Conolly, Daues, Howard and Toups [9] in relation to well-known Technology Readiness Levels (TRLs). For them a (Lunar Surface) Habitation System is *"the integrated set of habitation assets to support a crewed mission and ensure a safe, productive, pressurized environment for human habitation."* Correlations between HRLs and TRLs are a good example how a human-centered design approach can be integrated into already established technical methodology.

All these definitions imply that the job of a space architect is to create an environment that is safe and comfortable for people to live and work, and return back home in a good physical and psychological state.

4 Current Educational Practices in Aerospace Design

Space-architecture and aerospace engineering practices have different approaches for identifying a problem and solution finding. Architecture and engineering disciplines also have different educational approaches with different tasks assigned. The same can be observed in other disciplines such as medicine, industrial design, physical sciences, etc. To achieve better integration of space architecture' objectives into engineering and architectural curricula both approaches need to be examined and assessed.

Interdisciplinary design processes add complexity when the goal is to create an optimized design that is compatible with mission goals, technological, scientific, design, and human factors requirements.. Designing a crew habitat for outer space, surface of Mars, or any other extra-terrestrial body is one of the biggest challenges for space architects and engineers. Interdisciplinary communication is vital for successful and efficient design and interactions between all parties involved in design and planning activities.

However, often disciplines and practices use different terminology and acronyms identifying entities, objects,

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Task	Engineering Approach	Architectural Approach
Problem Definition	Product-oriented	Process-oriented
Approach	Linear(analysis) Start at the beginning of the process	Nonlinear and iterative (synthesis) Start at critical points, then adjust
Workflow	Workflow from the start to the end Done with numbers (quantitative methodology)	Workflow anywhere in the project Done with models (qualitative methodology)
Solution	There is one ideal solution Most decisions are quantifiable	There are many solutions Some decisions are quantifiable

Table 1. *Engineering and architectural approaches throughout processes. (Adapted from Brand N. Griffin)*

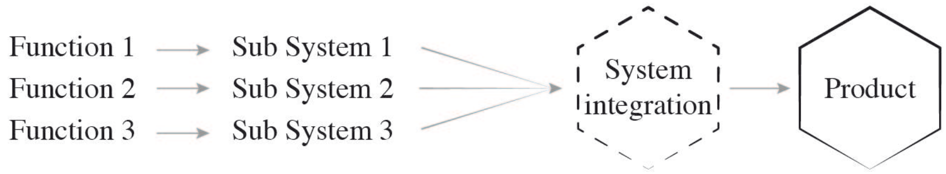

Figure 1. *Example of a common engineering design approach*

and functions. For example, even the meaning of a term 'design' differs between engineers and architects.

Misuse of terms and definitions can create confusion and misunderstanding, which may lead to significant design flaws and errors affecting overall planning and mission success. Table 1 shows examples of how different tasks can be understood by architects and engineers. In general: ways of identifying a problem, perceiving it, and finding design solutions can be quite different [11].

Engineering classes focus on learning about systems, subsystems, elements, and parts. Students understand connections between them in order design a system that performs a particular function for which those systems or units are designed. The engineering approach, illustrated in Fig. 1 uses system and sub-system requirements as constraints for the system. Each function is determined by a trade-off process. The organizational stage includes function determination and prerequisites. It is followed by generalized requirements, and the integration stage usually becomes a part of the process in professional system engineering practice. System engineering is dealing with a system as a whole and connects the traditional engineering disciplines. It also includes the evolutionary process of maturity levels [12, 20, 19].

A drawback of this approach may be the neglected human factor when it is not treated as an equal system element. The International Space Station is an example of an engineering design approach.Important human factors and habitability elements have been discarded in an early stage (eg. habitation module) or have been added very lately to the station (eg. personal crewquarters).

5 Space Architecture Educational Approach

"Engineers think architects make things prettier, difficult to build, and more expensive. Some can, but space architects are different. They analyze like an engineer and synthesize like an architect" [13].

The space architecture approach combines engineering thinking with criteria related to habitability and human factors, such as considered in architecture and industrial design, plus including other disciplines such as medicine and sciences.

When introducing architecture students to a design studio in Space Architecture, Marc M. Cohen states that: *"[...] it is always a challenge to orient them to the unique and peculiar characteristics of designing human habitation in vacuum and reduced gravity regimes.[...] The*

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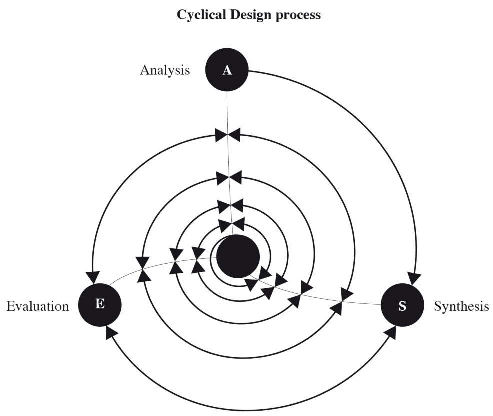

Figure 2. *Cyclical Design Process. (Original model by Donna P. Duerk, adapted by the authors)*

challenge is a difficult one, given the shortness of time for a quarter or semester, and the variety of the students' backgrounds, with some stronger or weaker in engineering, human factors, materials science, and physics.[…] Also, the students often start from differing levels of professional preparation and training, so it is inevitable that each one interprets the information differently and takes an individual and often idiosyncratic approach" [17].

Depending upon the overall topic (manned systems design, space structures and applications, lunar and planetary exploration, and terrestrial analogues) students usually start with extended research of relevant topics that include mission architecture, human factors, ergonomic influences, extreme environments, constraints and influences, and psycho-social factors. They will attain a good understanding of the system and associated structures through design, research, and analysis of specific projects.

Certain creativity and the development of 'out-of-the-box options' can be helpful at the beginning. The architectural approach to project development is basically non-linear and based on the synthesis of inputs from multiple disciplines. Design process cycles will evolve through time and levels of development. Fig. 2 shows an example diagram of a cyclical design process.

Furthermore, the design process is interdisciplinary (Fig. 3) and related to:

- Systems' and elements' Technology Readiness Levels (TRLs) and Habitability Readiness Levels (HRLs)
- Availability of resources (physical and intellectual
- Timeframe
- Societal and political support
- Economic and environmental impacts. (Testing and feedback)

Interrelationships between design stages and involvement of different disciplines should be established throughout the design and production development (Fig. 4). Other diagrams address similar reciprocal design processes but depict it from different perspectives: the spiral process reflects an architectural synthetically enhanced approach and is based on a system engineering process. The multi-linear diagram reflects engineering and architectural team efforts in pursuing integrated design solutions.

6 Educational Examples

There is still a need for an appropriate educational approach to enumerate space architectural objectives in related disciplines. This section of the paper shows examples of academic courses and workshops that demonstrate the importance of multidisciplinary work in order to expand the potential of design scenarios towards future space exploration mission planning and spacecraft and structures design.

6.1 ESA Habitat Design Workshop

In 2003, a number of students and young professionals formed an initiative to promote interdisciplinary design processes. The initiative was triggered by the lack of academic options and to follow up several personal meetings at different conferences. In 2004 this multidisciplinary highly motivated team of young architects, engineers, industrial designers and physicists from Austria, Italy, the Netherlands, England and Canada, known as the 'MoonMars Working Group' , began working on the idea of a habitat workshop. These efforts led to the Habitat Design Workshop, held on 2–9 April 2005 at ESA/ESTEC.

With the support of Piero Messina at ESA's Directorate for Human Spaceflight, Microgravity and Exploration and Bernard Foeing, ESA AURORA Program, the Moon- Mars Habitat Design Group put together an intense one-week programme based on lectures and

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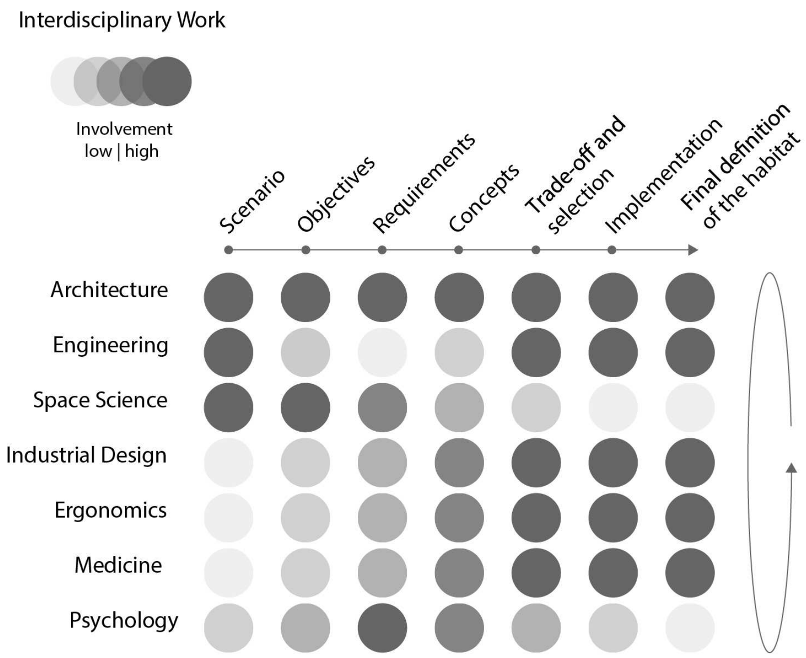

FIGURE 3. *Scheme of a disciplines relationships synthesized approach diagram*

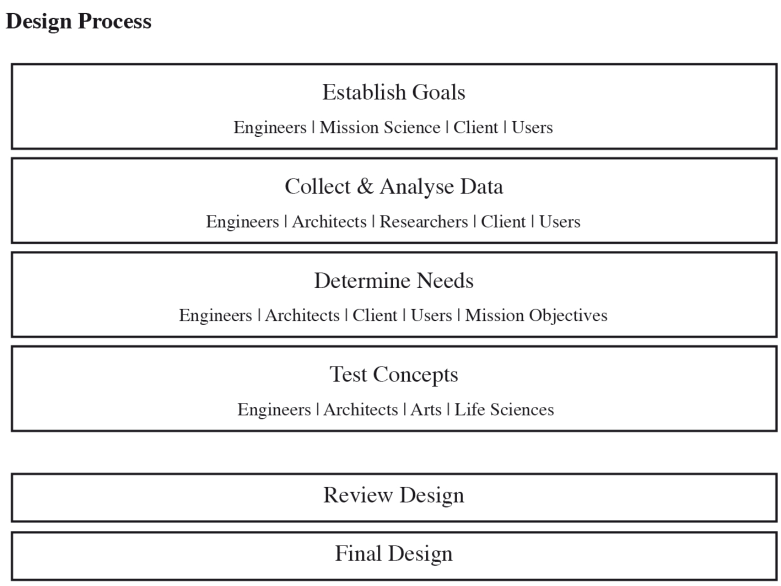

FIGURE 4. *Design process diagram. (Position paper on the role of space architecture [4])*

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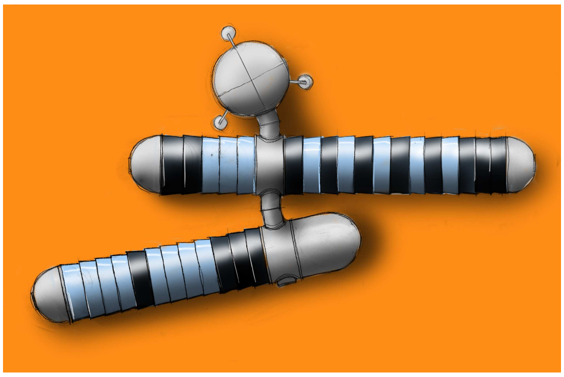

Figure 5. *The Elysium base presented a Mars outpost using soil and sand to make glass segments to be added to a pre-existing lander structure. (Team: B. Lansdorp, O. Clark, E. Sønneland, M. Gunter, G. Murph, K. von Bengtson)*

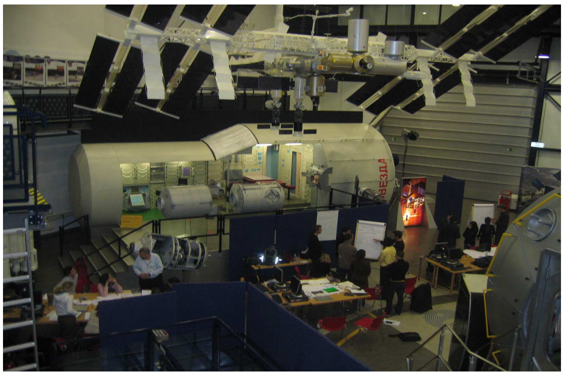

Figure 6. *The workshop and presentations of the ESA Habitat Design Workshop took place in ESTEC's ERASMUS facility*

group work, aimed not only at generating innovative designs but also at studying the group dynamics of a stressful, cross-disciplinary work environment.

The participants, 30 students and post-graduates were drawn from disciplines of engineering, medicine, physics, architecture and industrial design with the task to develop and design human habitation concepts. They could apply for one of the three scenarios: a base on Mars (an example is shown in Fig. 5), a base on the Moon, or an interplanetary transit vehicle that could land or "dock" on the Martian moon Phobos [23].

Following an extensive preparation of the participants via internet, the weeklong event was hosted in ESTEC's Erasmus Centre during the first week of April 2005 (Fig. 6).

The purpose of this work¬shop was to demonstrate the advantages of bringing together people from various disciplines at the very beginning of the design process. During that week, professionals from ESA and various space industries provided advisory for postgraduate students. The tight schedule foresaw an extensive lecture program in the mornings and working sessions in the afternoons and evenings.

At the end of the week, five final designs were presented to a final jury composed of ESA staff, industry representatives, and external experts and MoonMars organizers [23].

6.2 Space Architecture Design Studio

The TU Vienna is one of a few universities worldwide offering courses in Space Architecture that are integrated into the existing curricula of architecture. The design studio: 'Destination Moon' took part in the frame of the Master of Architecture program at the Vienna University of Technology (TU Vienna) in 2012. 25 students selected this one-semester program (March – June) and worked on their vision of a future research base on the Moon. All projects have been published and are available online for further information [17].

In the first phase of the studio a settlement strategy, based on a hypothetical scenario, had to be developed by the students. The emphasis of the second phase of the studio was on the actual design and implementation details of a lunar research station.

As most of the students had no previous knowledge in the field of Space Architecture, this course was accompanied by theme-specific lectures and workshops with space experts.

One of the biggest challenges for the students was that they could not rely on conventional architectural role models due to the total different physical and social environment. This mind shift and 'forced' critical thinking on basic questions like: *What is it for? What is happening there and why? can lead to real innovation – not only in the field of space architecture.*

In order to assess how well the students developed solutions, two kinds of reviews were provided: an internal one in the sense of a traditional studio review and an external one from the perspective of the larger world of human spaceflight. Space Architect Marc M. Cohen was invited to assess the feasibility of the projects in the professional practice of Space Architecture. The criteria encompassed three broad domains of evaluation: Concept, Representation, and Space Architecture Fea-

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Evaluation Themes	Explanation
Analogy, including Backstory	The use of analogy is a time-honored and widespread practice in architecture. Some students use analogy, but that is not a requirement in any sense. However it can add a story line and a degree of richness to the narrative.
Formal Concept	Developing such a concept as a discrete physical and visual form is an essential step in architecture.
Imported Philosophy	It has become fashionable in recent decades to start an architecture project from a philosophical – instead of a formal – parti (Point of Departure). Although the use of imported and possibly irrelevant philosophy sometimes provokes controversy, the recording here addresses only whether it is present in the project.
Structural Concept	Because Space Architecture occurs in the extreme environment of vacuum and reduced or microgravity, the structure must not only support conventional live and dead loads, but also the pneumatic pressure of the atmosphere.
Geometric Construct	As part of the structural concept or the formal concept, a geometric concomitant often becomes a prominent organizing principle.
Science of Physics Concept	Some Space Architecture concepts invoke innovative applications of science, most often physics, in developing a habitat project. However, often as much peril can accrue to the project as benefit unless the architect brings a solid grasp of the science to the effort.

Table 2. *Evaluation Themes for the Criteria CONCEPT for the Design Studio 'Destination Moon'. (Marc M. Cohen), as published in Destination Moon (TU Vienna, 2012) and Space Architecture Education for Engineers and Architects (Springer, 2016)*

tures, each divided into subthemes [17]. Table 2 gives an overview of the criteria definitions for the domain Concept.

Fig. 7 shows a visualization of the student project titled 'Twist'. The project 'Twist' creates a linear array of units that begins at the upper edge of a crater wall and follows the slope down towards the center. The form of these habitation units derives from the structure, which consist of a spiral spring. The crew will deploy this spiral inside the inflatable, giving it a form that provides volumes of varying shapes and sizes that can accommodate the living and working environment functions. The spiral will initially be flexible but its foam filling will harden into a rigid shape. This project got a good score in the domain Concept. Areas that needed further attention include the construction of the spiral to be further articulated, particularly the outer inflatable layer that would be filled with rigidized foam [17].

The domain Space Architecture Features encompassed a specific knowledge that students gained and applied in the studio. Evaluation themes for Space Architecture included multiple access, dual remote egress, multiple circulation loops, private quarters, work or lab area, plant growth area, life support, surface mobility, robotics and EVA access airlock [16, 17].

The 'Balloon in a bowl' habitat, featured in Fig. 8 consists of a deployable, hexagonal plan inflatable structure. It has an inner deployable / expandable framework. The functional modules include the Habitat, Greenhouses, and Regolith Processing. The Resistance / Residence pursues a philosophy of "environmental adaptation". The concept for an integrated inflatable and rigid structure that all deploys simultaneously is quite ingenious and the model explains it very well [17].

6.3 Prototyping, 1:1 Building and Field Simulation

In 2013, the design studio: 'Deployable Emergency Shelter on Mars' at the TU Vienna challenged the students to develop, build, and simulate an emergency shelter for Mars surface. The design brief requested an additional crew support element, with regards to potential EVA / science activities to be performed on Mars and related safety issues.

The primary feature had to be a portable and deployable shelter that can be employed in the event of an

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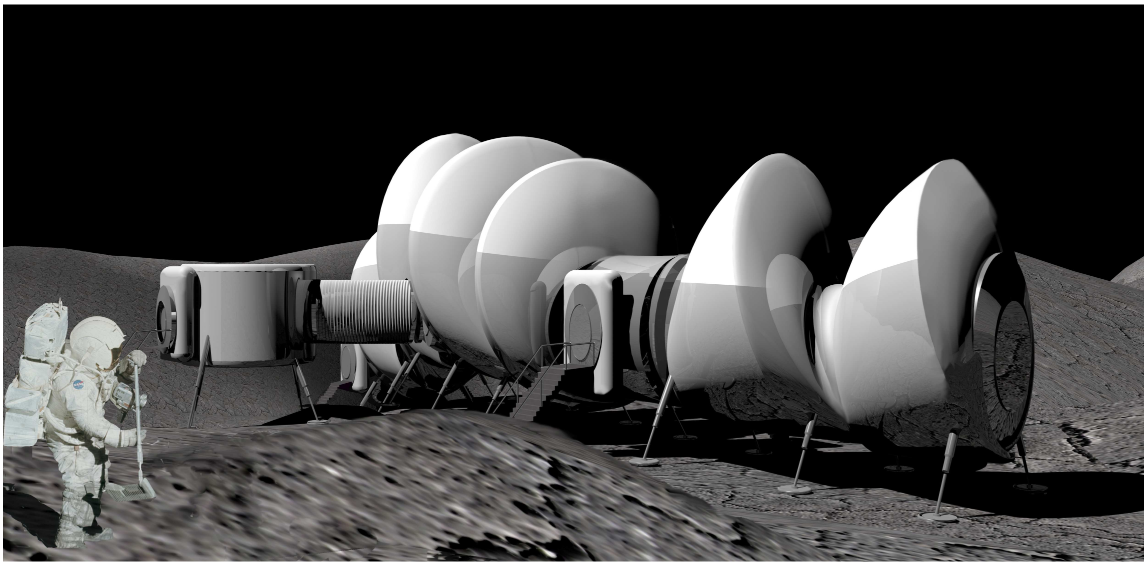

Figure 7. *Rendering of the project Twist by Daniela Siedler. Design Studio Destination Moon 2012 at the University of Technology, Institute for Architecture and Design, Department Hochbau 2. (TU Vienna, HB2, Siedler)*

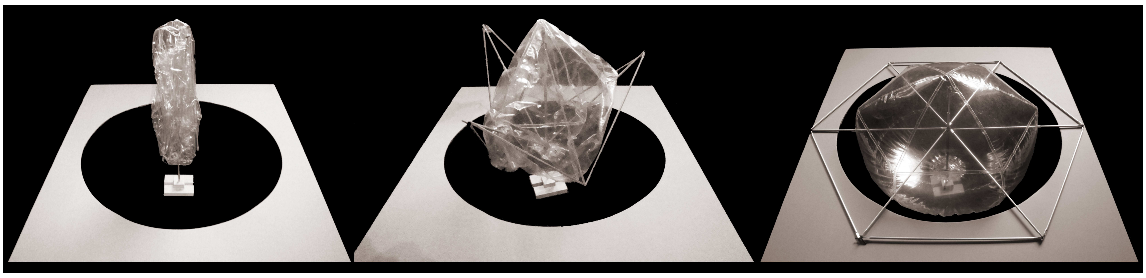

Figure 8. *Scale model showing the deployment process of the lunar base project Resistance / Residence undercover by Stefan Kristoffer. Design Studio Destination Moon 2012 at the University of Technology, Institute for Architecture and Design, Department Hochbau 2 (TU Vienna, HB2, Kristoffer)*

emergency requiring immediate action and where return to the base / rover is not possible in time.

Following the selection of prospective emergency scenarios and the definition of design criteria, a series of preliminary designs for an emergency shelter was developed within the HB2 academic design studio. In total three 1:1 prototypes were developed, built and revised (Fig. 9 and 10). The final prototype was tested during the Morocco Mars Analog Field Simulation in February 2013 as part of an operational evaluation of this deployable and portable multipurpose shelter. All design projects and the eventual prototypes have been published and are available online for further research [18].

The team at the TU Vienna chose a design-orientated approach along with a literature research of the state of the art and potential applications. Students were asked to work on emergency scenarios likely to happen on Mars and to develop the design criteria for the first models. Based on the most promising design, the first full scale prototype was developed and built. The second prototype was tested with the suit tester during a Dress Rehearsal Meeting in Innsbruck. The third mock-up was then tested during a field simulation in the Sahara, dealing with the three pre-defined contingency scenarios (Fig. 10).

Between the 1st and 28th of February 2013, the Austrian Space Forum (OEWF) conducted an integrated

Mars analogue field simulation in the northern Sahara near Erfoud, Morocco in the framework of the PolAres programme [18, 14]. The emergency deployable shelter was among the experiments preparing for future human Mars missions, conducted by a small field crew. The emergency scenarios were tested by a student team and the OEWF analogue astronauts during the analogue simulation mission (Fig. 12).A prototype was made to fit a number of human activities based on the most likely emergency scenarios during an EVA on Mars. Three selected emergency scenarios were tested during the simulation: One astronaut loses consciousness but is still breathing; Astronauts get exhausted and have to rest for a while; one astronaut falls down and suffers from a traumatic injury and/or space suit malfunction.

The evaluation was based upon a comparison between the shelter deployment behavior under controlled (laboratory) conditions versus the deployment in the field (to account for the influence of dust), as well as a subjective assessment of the developers, the on-site team including the analog astronauts and a post-mission inspection of the wear-and-tear patterns of the hardware. The evaluation demonstrated the expected good functionality of the mock-up. The deployment (pop up) worked as expected and took less than 1 minute. Opening (unzipping) the shelter was tested a number of times. Some difficulties were detected due to the small size of the zip pull tabs. Additional ribbons were then connected to the pull tabs allowing easier use with the space suit gloves. The deployment on a slope and rocky surface worked well.

The prototype was designed to allow functional adaptability including the adaption of the sitting and lying positions for the astronauts. The change between the two positions is achieved through air shifting between two supporting pneumatic cushions, one in front and one in the back of the shelter. The change between the two positions was tested with two astronauts inside the shelter. The mechanism worked well and efficiently. The analogue astronauts reported that sitting in the shelter was very comfortable and allowed them to fully relax. The sitting height was sufficient. The measurements of the astronauts CO_2 levels (carried out by the ÖWF) support this finding.

6.4 European – American Academic Collaboration

STAR Design is a cooperative program between NASA Johnson Space Center and the Lund Institute of Technology, Sweden that began in 1998. Each year is a different focus for the students. Architects and industrial designers from Lund have been participating in the NASA educational outreach program STAR Design since its beginning. Lund professors Per Liljeqvist (Industrial Design) and Tina-Henriette Kristiansen (Architecture) and their students worked on the development of innovative crew habitation systems and elements that could help in realizing ambitious plans of deep space exploration.

Figure 9. *Students simulate several procedures in order to adjust suitable body positions and to get a feeling for spatial and functional requirements. Design Studio Destination Moon 2012 at the University of Technology, Institute for Architecture and Design, Department Hochbau 2. (TU Vienna, HB2)*

As part of the program, the students spend two weeks during fall semester at NASA Johnson Space Center in Houston working with professionals from NASA, its Exploration Systems Engineering Office and the Advanced Extravehicular Activity Team. They also acquired space architecture design approaches by visiting SICSA (Sasakawa International Center for Space Architecture at the University of Houston). There, students learned about the human spaceflight program and developed their design concepts, with an emphasis on human needs, space environment, and its challenges for people and spacecraft design.
Larry Toups, from the Exploration Systems Engineering Office, oversees the program at JSC. According to him, the students' work could help NASA in agency's preparation for future missions to the Moon and Mars. Similar to the International Space Station and earlier US and Russian stations, the habitable volume of a structure on the Moon or Mars will be limited and much planning must take place in order to use that space as ef-

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Figure 10. *Last pre-test with the analog astronauts at the Austrian Space Forum. (OEWF, Zanella-Kux)*

Figure 11. *Last pre-test with the analog astronauts at the Austrian Space Forum. (OEWF, Zanella-Kux)*

ficiently as possible. (Fig. 12)

6.5 European – Russian Academic Collaboration

The annual International Youth Science School 'Space Development: Theory and Practice' has been running since 1997 at the Bauman Moscow State Technical University (BMSTU) with support from Ministry of Education and Science, and Russia's Federal Space Agency. Since then more than 2000 Russian and international students participated in the program. Many of them are already working on space projects in leading aerospace corporations and agencies of the world. Main educational element of the program is a group scientific project. Although participants of the school mostly come from engineering disciplines, it is open for all interested students.

Space architecture students from Houston and archi-

Figure 12. *Last pre-test with the analog astronauts at the Austrian Space Forum. (OEWF, Zanella-Kux)*

tecture students from Lund teamed up with aerospace, electrical, and robotic engineering students in several summer sessions developing creative design solutions for long-term manned space missions. Fig. 13 presents examples of their work. The students presented their results of the two-week team project to an external jury comprised of cosmonauts, MSTU professors, and industry professionals. Projects usually achieved a detailed schematic design stage.

7 Conclusion

The European-wide interdisciplinary approach has already proven its validity through the ESA Habitat Design Workshop in 2005 [23] and other academic programs in Europe and the US [17, 18]. The examples shown highlight how cross- fertilization among different disciplines can bring original solutions.

As a possible next step and with reference to current ESA plans of building a village on the Moon, the momentum can be used to continue and reinforce educational activities and networks with the goal to deliver innovative concepts for an international Moon village (and its associated technical, organizational, and social challenges).

For such a delicate international program, the inclusion of interdisciplinary educational activities is even more relevant as the same (old) difficulties and challenges of academic training still exist:

- Students and professionals are trained in space engineering but lack expertise in human factor derived requirements;

- Students and professionals in the fields of architecture and design are (often) not adequately prepared

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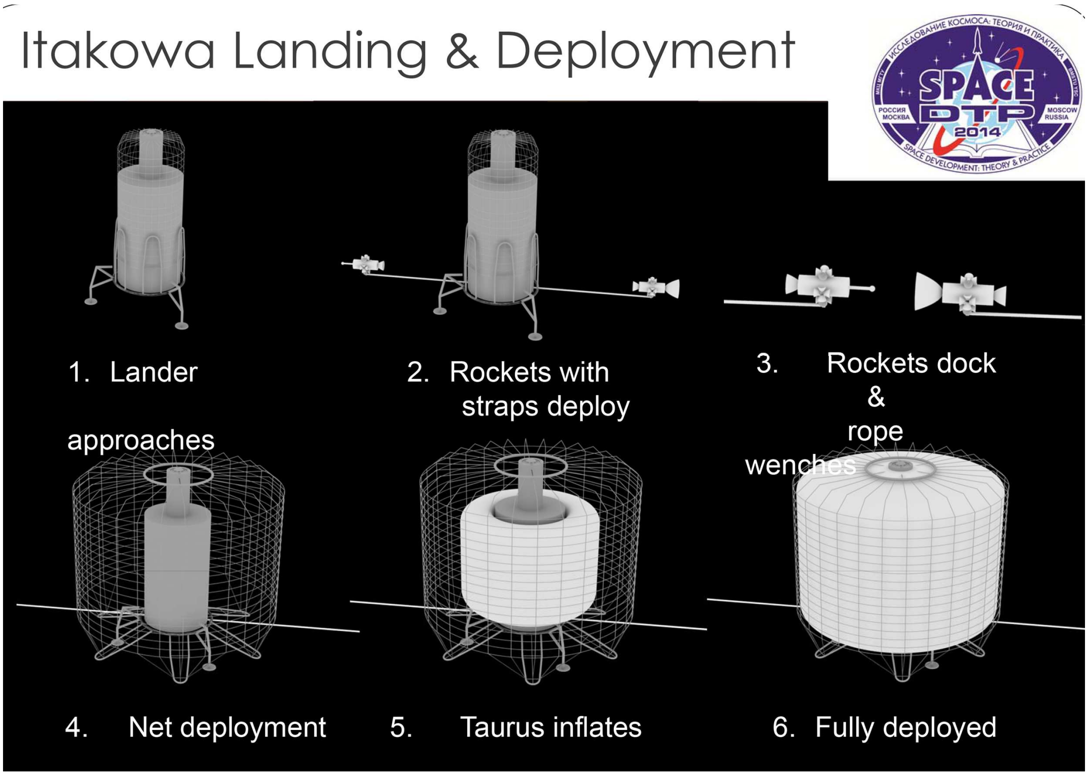

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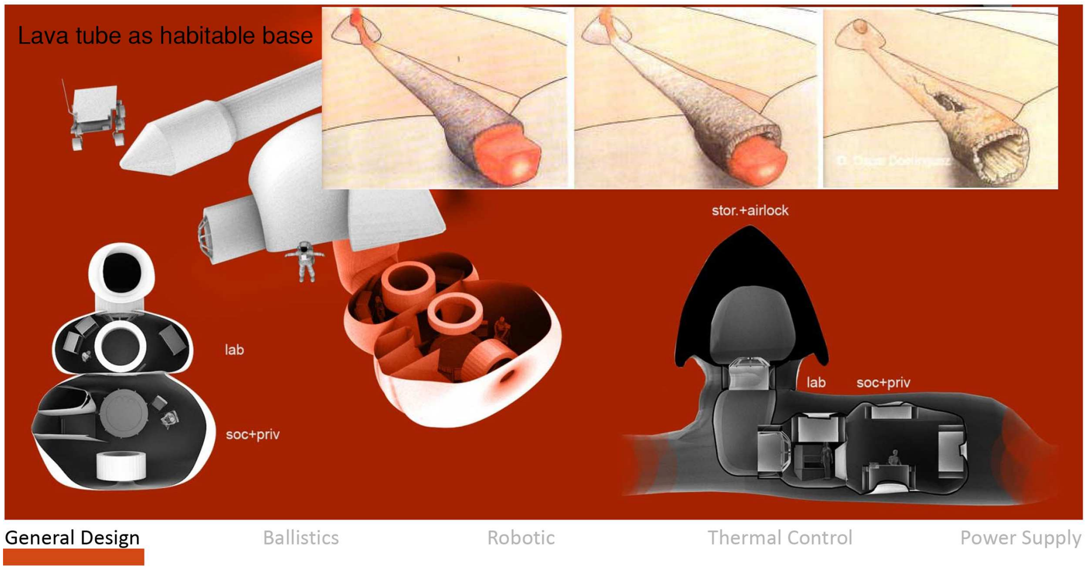

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Figure 13. *Mission to Mars: a – using an asteroid as a vehicle to Mars, habitat is docked to an asteroid; b – Mars surface habitat located in a lava tube*

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with respect to engineering requirements and evaluation criteria;

- Interdisciplinary interaction is challenged by different research and working methods;
- Different vocabulary is used for the identification of design problems and requirements, and evaluation criteria that are often inconsistent.

A multidisciplinary working approach within a workshop, design studio and alike can ignite to overcome many of these challenges that are so vital for every day work processes and results. In addition, the whole space community would benefit from new ideas derived in the workshop and through network building. The experience of such an interdisciplinary program – as part of the curricula - would help to train aerospace engineers with an understanding for the requirements related to human factors, as well as architects with the knowledge in aerospace engineering. Furthermore both professions will be introduced to the 'art of critical thinking and decision making'.

The authors have recently published a book to prepare students quickly to overcome first challenges in their learning experience. The book 'Space Architecture Education for Engineers and Architects' (Springer, 2016) takes on the mission of teaching students to design a space habitat and evaluate it at an HRL level 3. This means that the book should furnish lessons that will enable the student/reader to research, do task analysis, develop an operational concept and mission timeline, decide on areas, volumes, and adjacencies for activities and equipment, and to design lighting and other habitation systems using CAD, scale models, and drawings as appropriate.

As the former NASA astronaut Dr. Bonnie Dunbar put it, space exploration *"is no longer science fiction, but is science and engineering fact. We have also learned that space exploration is complex and very unforgiving of error. Designing spacecraft and space and planetary habitats for humans requires knowledge spanning a range of disciplines: engineering, medical sciences, psychology, human factors, life support systems, radiation protection/space weather, and other extreme space environments, at a minimum. These disciplines must result in an integrated human centered system, which should also be reliable, safe, and sustainable. This is space architecture"* (Foreword of the Book: Space Architecture Education for Engineers and Architects, 2016, by the authors).

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