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Series Editor: Douglas A. Vakoch

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Space Architecture Education for Engineers and Architects

Designing and Planning Beyond Earth

Springer

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Foreword

Space Architecture as a Discipline

When author Jules Verne wrote “From the Earth to the Moon”[1] in 1865 and “Around the Moon”[2] in 1870, he conceptually designed rockets and human space habitats in order to explore the moon. His imagination was remarkable, at that time in history there were no functional rockets, satellites, or even airplanes. Yet, Jules Verne thoughtfully considered the many dimensions and variables of humans living in the extreme environment of space and applied the laws of physics known at that time. His escape velocity was remarkably close. Many of his concepts of the environment of space were prescient. Certainly he captured the imagination of many people during the following 150 years. He influenced generations with his passionate writing about science and exploration. How much did he influence the future? During the last 60 years, the United States has landed 18 men on the surface of the moon; the US, Russia, and China have launched over 400 humans into Earth's orbit; the US and Russia have built complex permanently occupied space stations; an International Space Station (ISS) with more than 20 member nations now orbits the Earth; and China is poised to build its own space station within the next decade. On the horizon, India plans to launch humans into space for the first time. As the ISS passes its 15th anniversary, the eyes of many nations are once again turned towards the moon as a permanent research base, and the next step towards landing humans on Mars. What will the spacecraft and stations look like? How will they be resupplied? What will be their primary functions? How will in situ resources be integrated? How do we support psychological needs of crews who may be away from Earth for more than 2 years? “Space” is also now a tourist destination. How will designs change for a commercial space and tourism?

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[1] Novel by Jules Verne, first published as De la Terre a la Lune (1865).

[2] Jules Verne’s sequel to “From the Earth to the Moon”, first published as Autour de la Lune (1870).

This 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.

In the first 50 years of spaceflight, "Space Architecture" evolved within the organizations and companies tasked with implementing the missions. Engineers and scientists trained and educated themselves. As the next generation of humans assumes its place in the inevitable pursuit of new exploration horizons, it is time to provide a textbook for students that captures the collective experience, knowledge, and wisdom of those who have paved the way, step by step. This book does just that—addressing all steps of the design process from mission planning, to design validation, demonstration and testing, to operations. Who knows what the future will hold? Perhaps, in the next 150 years, Space Architecture will be a degree offered at most universities, with its own certificated licensing requirements.

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Preface and Acknowledgments

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Chris Welch on ‘The Essence of Interdisciplinarity’ in Chap. 1 Introduction.
Brand N. Griffin on ‘The Role of the Space Architect’ in Chap. 2, Chap. 4 and the Appendix.
Brent Sherwood on ‘Space Architecture Education—Site, Program, and Meaning’ in Chap. 2.
Marc M. Cohen on ‘Mockups 101: Technology Readiness Levels for Mockups and Simulator’ in Chap. 3.
Madhu Thangavelu on ‘The Moon or Mars: Where might we settle first?’ in Chap. 3.
Theodore W. Hall on ‘Artificial Gravity and Implications for Space Architecture’ in Chap. 4.
Lobascio Cesare on ‘Environmental Control and Life Support Systems’ in Chap. 5.
Haym Bennaroya and Leonhard Bernold on ‘Engineering and Construction of Lunar Bases’ in Chap. 5.
Kriss J. Kennedy on ‘The TransHab Project’ in Chaps. 5 and 6.

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Contents

Chapter 1
Introduction

Abstract Space Architecture is interdisciplinary and connects diverse fields such as aerospace engineering, architecture and design, human factors design, space sciences, medicine, psychology, and art. It therefore 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. This book is structured around basic learning processes for the design of a space mission, structure, or vehicle. The chapters on the design principles are related to the Technology Readiness and Habitation Readiness Levels—TRLs and HRLs (refer to Chap. 3: Comprehensive Planning) and include examples, discussions, and tasks. Examples are given to students for further individual research and assessments. Although the authors offer multiple examples in some chapters, there are many more to research and evaluate.

1.1 The Field of Space Architecture

> Space Architecture is the theory and practice of designing and building inhabited environments in outer space (SATC 2002, p.1).

This mission statement for space architecture was developed at the World Space Congress in Houston in 2002 by members of the Technical Aerospace Architecture Subcommittee of the American Institute of Aeronautics and Astronautics (AIAA).[1]

Following the quotation above, *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 required infrastructure. Earth analogs for space applications, simulation and test facilities are also included in the field of Space Architecture. Earth analogs may include Antarctic, airborne, desert, high altitude, underground, undersea environments, and closed ecological systems.

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[1] The authors were among the attendees/signatories of the Millennium Charter which was drafted by 46 architects, engineers, industrial designers, managers, and researchers; The entire text of the Millennium Charter document can be downloaded via spacearchitect.org.

S. Häuplik-Meusburger and O. Bannova, *Space Architecture Education for Engineers and Architects*, Space and Society,
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Space Architecture, as a discipline, is not new but has been emerging for at least 40 years. When NASA and the former Soviet Union turned their views towards long-term human missions, space architects and designers were involved. There is an abundant history of early design contributions to space projects.

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". (NASA [Issues] 1967, p.4) In 1968, Dalton and Raymond Loewy, a world-renowned industrial designer, worked on the Saturn-Apollo and Skylab projects. Loewy suggested a number of 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 (cf. Compton and Benson 1983). Dalton prepared the Skylab Experience Bulletins. Later he was project engineer for the Space Station module (1971). From 1965 to the 1980's Soviet Union's space systems, the 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 in the project. Lunar base "Zvezda" was part of that work (1960–1980). Perhaps the first female space architect was Galina Andrejewna Balaschowa.[2] She started at 57 at the Experimental Office OKB-1 as an architect and moved a few years later to the space architecture department, where she worked closely with Korolev. She designed Sojuz spacecraft, and Salyut and Mir stations.

Space Architecture is interdisciplinary and connects diverse fields such as aerospace engineering, architecture and design, human factors design, space sciences, medicine, psychology, and art. It therefore 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 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 environment and how to do so creatively.

Sources for Further Research on the History of Space Architecture:

- Book "Space Stations—base camps to the stars" by Roger D. Launius (Konecky and Konecky 2003)
- Book "Architecture for Astronauts—An Activity based Approach" by Sandra Häuplik- Meusburger (Springer, 2011)
- Book "Living in Space: From Science-fiction to the International Space Station" by Giovanni Caprara (Firefly, 1998)
- Book "Living and Working in Space: A History of Skylab" (Compton and Benson 1983)

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[2] Галина Андреевна Балашова (Rus).

- Book "Galina Balaschowa—Architektin des sowjetischen Raumfahrt programms" by Philipp Meuser (in German, with many illustrations of original drawings on Salyut and Mir space station interior; DOM Publishers, 2015)
- Book "Moon—a step towards technologies for Solar system exploration" editors Victor Legostaev and Vitaliy Lopota (in Russian, Луна – шаг к технологиям освоения Солнечной системы; 2011)

1.2 Structure of the Book

This book is structured around basic learning processes for the design of a space mission, structure, or vehicle. The chapters on the design principles are related to the Technology Readiness and Habitation Readiness Levels—TRLs and HRLs (refer to Chap. 3: Comprehensive Planning) and include examples, discussions, and tasks. Examples are given to students for further individual research and assessments. Although the authors offer multiple examples in some chapters, there are many more to research and evaluate.

This chapter briefly describes the history and field of space architecture with additional sources for further reading. This chapter introduces the reader with the structure of the book and how to use it in a class environment or for personal education.

Chapter 2, discusses differences in educational practices in architecture and engineering disciplines and addresses them through a space architecture philosophy. The purpose of this is to help educators and students who come from different backgrounds to understand each other and the multidisciplinary nature of space flight design and planning processes. The chapter includes descriptions and analyses of architectural and engineering educational approaches, comparing research and design processes, and providing examples of each.

Following the Approaches and Methods is Chap. 3, which addresses mission planning and building an exploration strategy. Mission types, requirements, and constraints, as well as current and future missions' goals and objectives are given as references for students and teachers to use in class and class projects. This chapter introduces students to the practice of applying Technology Readiness Levels (TRLs) and Habitability Readiness Levels (HRLs) to assess any technology or a habitation system.

Chapters 4–6 correlate with the structure of Technology Readiness Levels (TRLs) and Habitation Readiness Levels (HRLs) described in Chap. 3.

Chapter 4, covers design research fundamentals and prerequisites including human factors, environmental characteristics, and influences on design and human activities. This chapter also talks about Technology Readiness Level 1 and Habitation System Research Level 1.

Chapter 5, discusses site selection procedures, habitat concepts, and their structural and construction characteristics, plus habitability support systems principals. This chapter relates to Habitation System Research and TRLs and HRLs 2-3.

Chapter 6, describes functional allocation strategies along with development of verification methods. The chapter also introduces technology and technology operations. Examples are drawn from reduced and full-scale models and low and high fidelity mock-ups, including the International Space Station. This chapter relates to Habitation System Research and TRL and HRL 4–9.

Appendix includes glossary with common aerospace and space architecture abbreviations listed and explained; hints for students who want to know more about the Space Architecture discipline, schools that offer related programs, and index of names and organizations used in the book.

1.3 Benefits for the Reader

Based on the authors' experiences in teaching, this book was prepared with the intention to help students quickly overcome the first challenges in their learning experience. This book is also to help space architecture, architecture, and engineering educators understand a multi-disciplinary approach and to cross-introduce architectural and engineering objectives into their curricula. The authors recommend that the field of Space Architecture should become integrated into Aerospace curricula and should become part of architectural schools as well. It will greatly contribute to the ability of students to think critically.

The book 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.

This book is reaching out to future mission planners, engineers and architects, and all professionals involved in the design for manned spaceflight to enable them to:

- Learn about space systems and human factors as equal elements of a spacecraft and mission design;
- Acknowledge 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;
- Address relationships between human behavior and built environment;
- Interact successfully with diverse fields and disciplines throughout the project's lifecycle.

In summary, this book addresses problems and challenges of academic training that include (cf. Robinson et al. 2008):

- Students and professionals who are trained in space engineering but lack expertise in human factor derived requirements;
- Students and professionals in fields of architecture and design who are not adequately prepared with respect to engineering requirements and evaluation criteria;
- Interdisciplinary interaction that is challenged by different research and working methods, different glossary used for the identification of design problems and requirements, and evaluation criteria that are often inconsistent.

This book will assist students to achieve or master the following skills:

- Thinking and working in multi-disciplinary processes that stimulate team leadership skills—and can be applied in other aerospace fields;
- Understanding connectivity between different levels of interaction between human beings and machinery;
- Simultaneous mission planning approach and critical thinking;
- Reflections and correlations between disciplines involved in planning and executing space exploration missions;
- Knowledge gained from different disciplines through cross-applying and re-applying design approaches between *various* space-related fields of study and research.

1.4 How to Use This Book

This book is written to help students at every stage of the learning process. It can be read from the beginning to the end, but also can be used as a lexicon to look up principles and get more inspiration for personal achievements.

> Experienced space architects realize that rarely does the first mark or decision remain unaltered throughout the entire process. Therefore, it doesn't matter what the first step is, as long as the process is flexible enough to permit change. The process is cyclical so there are multiple entry points around the loop. The key to overcoming the terror of the blank page is to begin anywhere, with anything (an estimate, a trial mark, a guess) and then react to that initial decision (Griffin 2014, p. 4).

Class instructors and students can find in this book reference materials, historical examples, ideas for projects, and seminar discussions. The authors present *Discussions and Tasks* sections in Comprehensive Planning and Design Principles for the evaluation of students' understanding of the material and to stimulate creative and critical thinking in the class.

1.5 Guest Statement: The Essence of Interdiscliplinarity (Chris Welch)

At its crux, space architecture is a manifestation of humanity's desire to explore, to journey out into the universe, and to change the new spaces that we find there into new places for us to be. As for any journey, there is a departure from the well known and familiar; a movement into new and potentially challenging areas, combined with a willingness to engage with change.

Journeys can be physical, but they can also be mental. As we move forward into the 21st century, our understanding of the universe continues to evolve: our need to engage with the significant issues of our time requires us to transform our approach to dealing with complex problems. Since complexity implies many parts interacting in many ways and involving many disciplines, researchers and practitioners must be prepared to move away from the traditional disciplinary territories in which they have grown. They must start to explore new places, new languages and new ideas; engage with them, and discover what emerges from this dialogue.

This is not necessarily an easy undertaking. Modern academic and educational life revolves around research, practice, and teaching. The organizations that support these are, in the vast majority of cases, framed in terms of quasi-monolithic academic disciplines—areas of knowledge and expertise, branches of learning or similar, taken by their adherents to be in some way clearly distinct from other disciplines.

Historically, it is arguable that it was the Greek philosopher Aristotle who first created this separation between disciplines, at least as far as Western thought is concerned. Aristotle placed different types of knowledge into one of three categories, depending on their purpose.

At the highest level were the 'theoretical' disciplines such as theology and mathematics. These were to be pursued for their own sake. Aristotle then placed 'practical' disciplines such philosophy and ethics, to be undertaken in order to promote good judgment and decisions, in second place. In the lowest category were the 'productive' disciplines such as engineering and art.

Although not as rigid as might be supposed, implicit in this approach to classification is the idea that some disciplines are more 'useful' than others and that this may be used to establish comparative merit. Despite being a very culturally dependent artifact, the effect of Aristotle's system has lasted many centuries, creating a taxonomically-based approach to knowledge and the systems underpinning it. In particular, towards the end of the Renaissance and into the 17th and 18th centuries, European society became ever complex. As ever-increasing amounts of knowledge were developed, systems were needed to structure and organize it in ways that would allow it to be transmitted to the next generation as effectively as was possible at the time. Since it was no longer possible for a single individual to know everything (even if only in theory), individuals had to focus on subsets of 'total knowledge'. Inevitably, individuals with common interests formed discipline-based communities, which focused their attentions more inwards than outwards, with particular modes of enquiry and working being developed and codified.

This was perhaps most obvious in the sciences. The development of the scientific method encouraged practitioners to focus very narrowly on the subject of experiments in order to minimize outside influences that could make the results too complex to evaluate. At the same juncture, the outcomes of these experiments were applied to the development of new techniques and capabilities, which in turn stimulated new economic developments. In the form of the Industrial Revolution, this then reinforced the perceived value of the different disciplines.

Simultaneously, the view of the world—and, by extension, the universe—that science was apparently revealing to humanity was one, not only of a great mechanism, but one which was governed by and operated on the basis of a relatively limited number of physical principles which it was thought might be fully discovered and apprehended in due course. In such a situation, it is perhaps not surprising that discipline communities saw little need to communicate outside of their own groups—an attitude that has taken—and is, arguably, still taking—a long time to dissolve.

However, in due course this narrow-focus disciplinarity itself, revealed through quantum mechanics, molecular biology, and similar fields, that the universe is not as easily understandable as was thought and that it features not only complexity, and subtle interactions between its different elements, but also the potential for a variety of forms of emergent behavior that humans are only at the start of being able to comprehend.

At the same time, the rapid (in geological terms), and frequently anthropogenic, changes to the world and its environment, combined with the accelerating impact of human beings on the world, their society, and themselves, means that we are faced with increasingly complicated issues that cannot be engaged with or addressed in purely disciplinary ways. These issues require us to deploy additional knowledge that, as yet, we do not have and will not be able to discover using disciplinary techniques alone. This is why interdisciplinarity is so very important.

The essence of interdisciplinarity is that it must not only cross the borders between disciplines and their respective cultures but that—at its core—it must be transformational and change those disciplines that it links together. At the same time, unlike multidisciplinarity, it must aim to produce new ways of approaching problems and new forms of knowledge that lie outside our existing disciplines and their knowledge. As humanity faces the challenges of the 21st-century, interdisciplinarity is undoubtedly going to become increasingly important. The dialogue between different and hitherto unconnected disciplines is going to be essential in order to address the current issues that face us and also address new ones. Humans may be drawn to disciplinarity but the universe clearly is not. This approach has already been more than adequately demonstrated by the emergence of new 'interdisciplinary disciplines' such as bioinformatics which brings together the biological sciences, computing, and mathematics and without which our research into genetics and related disciplines would not be effective.

Another ‘interdisciplinary discipline’ is, as the authors of this book clearly state, space architecture. By its very definition space architecture fulfills the requirements of interdisciplinarity. Space architecture has a clear and pragmatic focus in that it seeks to advance our understanding of how to create places in space in which humans will thrive. Space architecture addresses complex issues and yet ones that, as presented in this book as approaches and methods, are clearly describable and which draw on the expertise and knowledge of many other disciplines. At the same time, the outcomes of space architecture require its findings to be re-integrated into the different disciplines involved in order to provide new solutions.

Consequently, all users of this book must anticipate both new insights and new understanding from outside their immediate backgrounds. They must also expect their prior knowledge to be put into sharper perspective by an interdisciplinary engagement with space architecture.

New possibilities await. The journey starts here!

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Chapter 2
Approaches and Methods

Abstract Space architecture as a discipline is relatively new, but it fills a gap between the engineering approach to design habitats and other space facilities for humans, and the complexity of human factors oriented design—including personal psychology, creativity, and non-work related activities. In order to successfully fill that gap, space architecture needs to be taught academically. This chapter talks about known and potential approaches and methods, drawing examples from current space architecture programs and classes, and representative projects. The authors consider that space architecture approaches to design and planning are important to be introduced to students who are coming from the diverse backgrounds of engineering and architecture. Other disciplines may benefit as well.

2.1 Introduction and Chapter Structure

This chapter addresses architectural and engineering approaches in educational practices. The two can be quite different and cause confusion. This chapter aims to enable students, faculty members, and other interested parties to acknowledge different approaches and therefore to help them better integrate their knowledge in interdisciplinary spaceflight related design and planning processes. A guest statement at the end of the chapter from Brand Griffin[1] talks about key positions of space architecture as a discipline.

Many universities around the world offer aerospace engineering undergraduate and graduate programs, but only a few relate to the field of Space Architecture.[2] This chapter presents examples of educational practices illustrated with student projects from European and American academic institutions that offer space architecture as a mainstream or major component in their curriculum.

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[1] Advanced Concepts Office at NASA's Marshall Space Flight Center, Space Architect.

[2] A selection of schools and universities offering courses on Space Architecture are listed in the Appendix.

S. Häuplik-Meusburger and O. Bannova, *Space Architecture Education for Engineers and Architects*, Space and Society,
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The chapter concludes with a guest statement from Brent Sherwood[3] where he talks about Space Architecture Education—Site, Program, and Meaning.

2.2 Future Tasks and Upcoming Challenges

Unlike early space missions, future spacecraft design concepts will not be based mainly upon engineering and structural requirements (cf. Brown 2002). Humans in future long-duration spaceflight and exploration endeavors will be assigned vital roles in the system. Therefore 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. Today's students and future spacecraft designers need to be prepared for the challenge of planning human missions and designing appropriate artifacts.

Table 2.1 illustrates that design considerations for many mission aspects change significantly in relation to missions' lengths and destinations. It is evident, that all mission aspects have influences on the design and vice versa:

- 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.

The importance of integration of human factors and other human-related aspects into the design process has been recognized by institutional parties.

The US Department of Transportation states the following concerning the modernization of the National Airspace System (NAS): "*The integration of human factors into the development and procurement of … new systems is vital to the success of the future NAS. Although the Human Factors Design Guide* (HFDG 1996) *has been available for a number of years and provided vital information, it did not have the weight and impact of a design standard. Instead, the Military Standard* (MIL-STD 1989) *was commonly cited in Federal Aviation Administration (FAA) system specifications.*" (Ahlstrom et al. 2003, pp. 1–1)

Although the statement above refers to current Federal Aviation Administration FAA practices (Wagner et al. 1996, pp.1-1–1-3), an analogy can be drawn for current space systems' and facilities' design approaches with more weight given to human factors and human activities-oriented design. Broader understanding of human-related physical and psychological impacts on design solutions and understanding how design can be used for mitigation purposes are critical for success of future exploration missions.

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[3] Strategic Planning & Project Formulation, NASA Jet Propulsion Laboratory, Space Architect.

Table 2.1 Comparison of mission aspects and design considerations of short missions (orbital) and long missions (Moon and Mars)

Missions aspects	Short missions (e.g. Orbital)	Medium missions (e.g. Lunar)	Long-term missions (e.g. to Mars)	Change of design considerations
Duration (months)	<6	6–12	>12	Habitat mass and volume
Distance to Earth (km)	300–400	350–400 K	60–400 M	Logistics mass and volume, increase of sustainability
Crew size	3–6	4≤	6≤	Size of habitat and logistics modules, privacy and social space
Degree of isolation and social monotony	Low to high	High	Very high	Interior design including privacy and social space (territorial issues)
Crew autonomy level	Low	Medium	Very high	Interior design with a certain flexibility to adjust to the crew needs
Emergency evacuation	Yes	Limited	No	Mission architecture and base/vehicle configuration
Availability of mission support				Mission architecture and habitat design, communication technology
Outside monitoring	Yes	Yes	Very limited	
Two-way communications	Yes	Yes	Very constrained	
Email up/down link	Yes	Yes	Yes	
Internet access	Yes	Yes	No	
Entertainment	Yes	Yes	Yes	
Re-supply	Yes	Very limited	No	
Visitors	Yes	No	No	
Earth visibility	Yes	Yes	No	Viewports

Modified from the source: Kanas and Manzey (2003)

When aiming to create an optimized design that is compatible with mission goals, technological, scientific, design, and human factors requirements, there is added complexity because of interdisciplinary design processes. 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.

Difficulties in understanding each other can arise between professions. Often disciplines and practices use different terminology and acronyms identifying

Table 2.2 Engineering and architectural approaches throughout processes

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

Adapted from Table 2.10 by Brand N. Griffin

entities, objects, and functions. Even the meaning of 'design' differs between engineers and architects.[4] That can create confusion and misunderstanding which may lead to significant design flaws and errors affecting overall planning and mission success. Table 2.2 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 (cf. Cross 1993).

2.3 Educational Practices

Different disciplines have different approaches for finding a solution. Although there are no canonical definitions of space-architecture and aerospace engineering practices, they have different educational approaches and often different tasks assigned. The same can be observed in other disciplines such as medicine, industrial design, and physical sciences, etc. This chapter discusses engineering and architectural approaches in order to achieve better integration of space architecture subjects into both curricula.[5]

2.3.1 The Engineering Approach to Habitation Design

> An engineer starts his design from a problem, i.e. from ignorance as non-knowledge. This corresponds to a question and indicates a direction towards an aim. Therefore the engineer needs knowledge concerning means as a functional compliance for an aim, knowledge of

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[4] Major terms that are used throughout this book are listed in the Appendix, in the Glossary section of the Appendix.

[5] Note: The authors highly recommend the inclusion of interdisciplinary team-oriented working processes at the university level.

> how to gain and to use such a means, knowledge concerning values behind the aim, and knowledge of how to modify the aim in the light of values, if necessary. (Michelfelder et al. 2013, p. 3)

Several specialized disciplines share an engineering approach. Two branches of aerospace engineering deal with a craft's design and all the components required for its successful implementation: aeronautical engineering concerns aircraft design for operations in Earth atmosphere; astronautical engineering relates to vehicles operating in space and on celestial bodies; others include civil, industrial, and maritime engineering.

Historically, space mission and craft design is based on an engineering approach that is called Systems Engineering. The International Council on Systems Engineering (INCOSE) defines it as follows:

> **Systems Engineering** is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. …Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs. (INCOSE 2015[6])

A goal of a system, as a group of elements that interact with each other, is to achieve specific common goals and to make the overall functionality better than the result of each element acting individually. According to Maier and Rechtin (2000, p. 8), "*systems are collections of different things which together produce results unachievable by the elements alone.*" Each system has its boundaries that separate it from the surrounding environment or from other systems. Elements and units inside the system are its basic components and if two or more of them have relationships they can be combined into sets based on the character of those relationships and become a subsystem of the main system. The description of a system as a whole leads to the three most important common characteristics that are present in all systems: *organization, generalization, and integration* (Chang 2011 p. 13).

2.3.1.1 Engineering Classes

Aerospace engineering students have to understand at least the principles of mathematics, physics, science, and engineering in order to design, construct, and test various types of aircraft and spacecraft. Engineering classes are focused on learning about systems, subsystems, elements, and parts. Students understand connections between them in order to perform a particular function for which those systems or units are designed. The engineering approach, illustrated in Fig. 2.1 uses

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[6] INCOSE—International Council on System Engineering. http://www.incose.org/AboutSE/WhatIsSE.

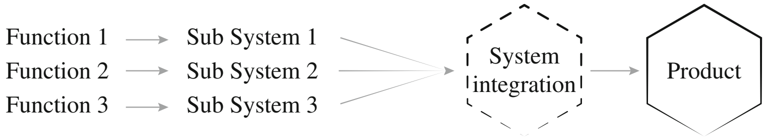

Fig. 2.1 Example of a common engineering design approach

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 (David 2013; Kossiakoff et al. 2011; Kesseler and Guenov 2010).

A drawback of this approach may be the neglected human factor if it is treated as only an equal system element. The International Space Station is an example of an engineering design approach. Important human factors and habitability elements have either been discarded in an early stage (eg. crew module) or have been added lately to the station (eg. personal crewquarters).

2.3.2 The Architectural Approach

> As a professional discipline, architecture spans the arts, engineering, and the sciences. Students must have an understanding of the arts and humanities, as well as a basic technical understanding of structures and construction. Skills in communication, both visual and verbal, are essential. While knowledge and skills must be developed, design is ultimately a process of critical thinking, analysis, and creative activity. The best way to face the global challenges of the 21st century is with a well-rounded education that establishes a foundation for lifelong learning.
>
> (ACSA [Goals] 2015[7])

The architectural discipline is multidisciplinary by its nature. It builds upon a basic understanding of engineering, esthetics, and social sciences. The level of such understanding depends on the complexity of the design problems and proposed architectural solutions. Architectural understanding of a design process includes problem examination, synthesis, and innovative pursuit. Developing skills in communication—both visual and verbal, is an essential part of architectural educational practice.

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[7] ACSA—Association of Collegiate Schools of Architecture. http://www.acsa-arch.org/about/about-acsa.

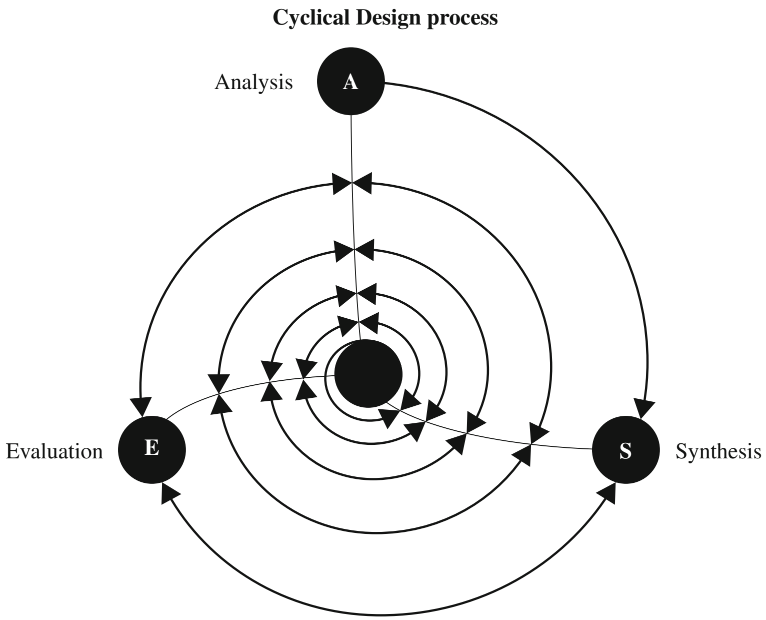

Fig. 2.2 Cyclical design process (original model by Donna P. Duerk, adapted by the authors)

2.3.2.1 Architectural and Design Studios

The architectural studio approach is based on a project-oriented strategy where students have to be creative in identifying required information and knowledge, analyzing it, and synthesizing the results into a final architectural design. The architectural approach to project development is basically non-linear and based on the synthesis of multiple disciplines.

Cycles of design process will evolve through time and levels of development. Figure 2.2 shows a diagram of a cyclical design process. "The design process is often seen as a serendipitous, cyclical process covering much ground at ever-increasing levels of detail at each sweep." (Duerk 1993, p. 10)

Brand Griffin also refers to a model for spiral evolution in his guest statement in Sect. 4.6, which originally comes from software engineering.[8] In terms of Space Architecture, it corresponds to the idea that at every design level all elements are considered, roughly at the beginning and more detailed at a later stage.

"Design is a cyclical process in which the designer or the design organization iterates a sequence of conception, representation, and evaluation until arriving at a satisfactory solution". (Cohen 1996, p. 2)

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[8] The original spiral model was developed by the software engineer Barry Boehm in 1986. Since then a number of variations do exist. (Boehm Barry. 1986. A Spiral Model of Software Development and Enhancement.)

Architectural training teaches students to operate at all scales from the "overall picture" down to the smallest details; to provide directive intention—not just analysis—to design opportunities, to address the relationship between human behavior and the built environment, and to interact with many diverse fields and disciplines throughout the project lifecycle.

2.3.3 The Space Architecture 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. (Griffin 2014, p. 2)

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 medicine and science.

During a space architecture studio, students advance and complete their individual projects for manned systems and habitat facilities aimed at optimizing human safety, performance, and comfort under extreme and confined conditions of space habitation.

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. Typically, the faculty presents a broad overview of the Space Architecture discipline, and to introduce the students to leading concepts and accomplishments. The 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.*" (Häuplik-Meusburger and Lu 2012, p. 4)

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.

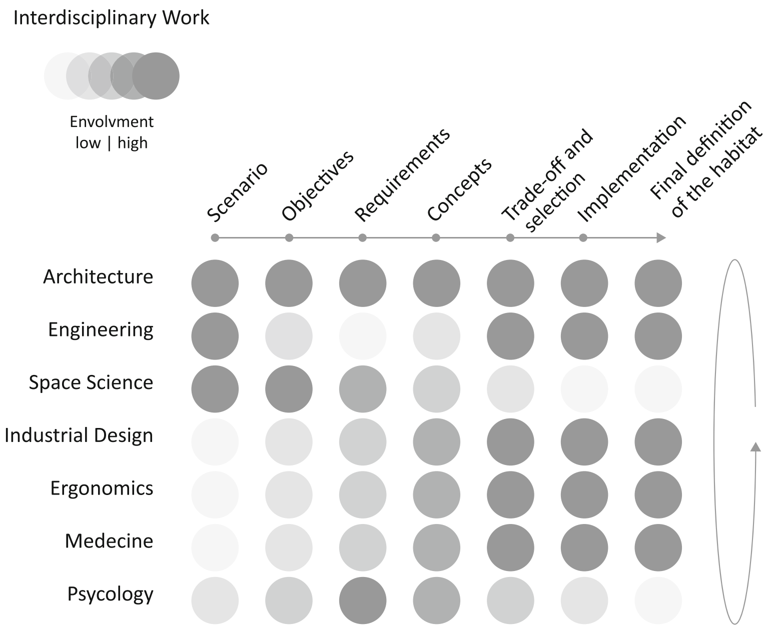

Fig. 2.3 Scheme of a disciplines relationships synthesized approach diagram

The design process is interdisciplinary (Fig. 2.3) and also 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 with involvement of different disciplines should be established throughout the design and production development (Fig. 2.4).

Many diagrams (e.g. 2.1 and 2.2) address similar reciprocal design processes but depict it from different perspectives: the spiral process reflects an architectural synthetically enhanced approach and is based on system engineering process. The multi-linear diagram reflects engineering and architectural team efforts in pursuing integrated design solutions. There are many more variations of these models and other ways of representation exist.

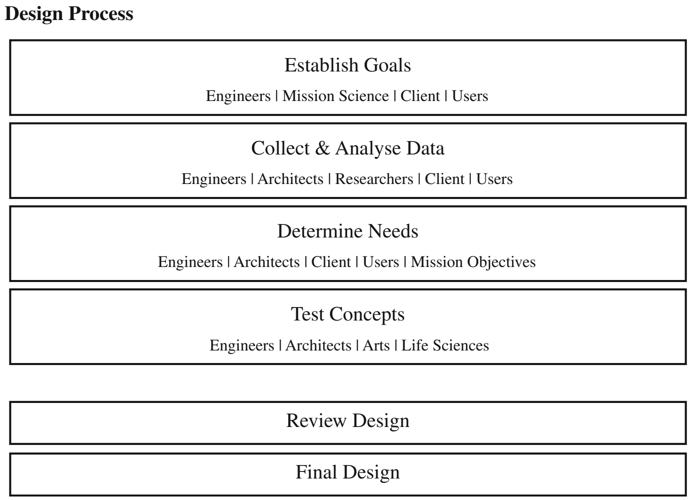

Fig. 2.4 Design process diagram (position paper on the role of space architecture, IAA 2013, p. 3)

2.4 Educational Examples

Although there is still a need for an appropriate educational approach to enumerate space architectural objectives in related disciplines, recent examples of academic courses, programs, and workshops show the benefits of integration to expand the potential of future space exploration mission planning and spacecraft and structures design.

2.4.1 Master of Science in Space Architecture Program (SICSA,[9] University of Houston)

MS-Space Architecture degree at the University of Houston was accredited by the Texas Higher Education Coordinating Board in 2003 after the first class of NASA professionals conducted their studies at the Sasakawa International Center for Space Architecture in 2001–2002 academic year (Table 2.3).

SICSA's central mission is to plan and implement programs that will advance peaceful and beneficial uses of space and space technology on Earth and beyond. Many of these activities address extreme terrestrial environments. The center offers two types of MS-Space Architecture curriculum, one for full-time students

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[9] Sasakawa International Center for Space Architecture, Cullen College of Engineering, University of Houston, Houston, Texas, USA.