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ABSTRACT

This paper describes an interdisciplinary approach to the conceptual design of space stations. Two key ingredients define it: a *human-centered* design approach, and a *habitat* attitude towards inhabited space structures. Both have their roots in terrestrial architecture, which represents centuries of experience in the design of human-centered habitats. The paper documents how an interdisciplinary conceptual design process was developed by improving an existing validated engineering methodology for the conceptual design of space stations by adding elements from architectural practice. An initial space station design project using this approach shows promising results.

INTRODUCTION

The conceptual design (project phase 0/A) of long-duration human-rated space missions poses significant challenges to the traditional design approach used for uninhabited or short-duration crewed missions [4]. Yet, the success of planned expeditions to Mars and beyond depends on the ability of mission designers to create an overall mission concept that maximizes crew efficiency and minimizes mission cost and risk of catastrophic failure, while at the same time integrating a wide array of technological, budgetary, political, and societal boundary conditions [30].

Space stations in low Earth orbit play a key role in the preparation of humankind's next "big step" toward other planets. They provide an ideal test bed for the final space qualification of new technologies and materials [20]. They also offer a close approximation of the environment that future planetary explorers will encounter during the long transfer flight to their destination, making them ideal training grounds for the crews of future interplanetary missions [28].

To maximize the value of such a space station for this type of utilization, the main design driver, implemented from the earliest stages of the design process, should be the most efficient integration of the crew and the adaptation of the mission to the crew's needs and limitations [5]. Thus, it is advantageous to see human-rated space structures – be they orbital or planetary stations or crew compartments of interplanetary transfer vehicles – not as "machinery-with-attached-crew" like earlier spacecraft [7], but primarily as habitats. This puts the focus on designing space stations *as* habitats, not on designing habitats *for* space stations – under the assumption that increased habitability leads to increased crew productivity, and thus mission success.

Due to the cost, complexity, and long program schedules of human-rated space missions, additional factors come into play that should be addressed as early as possible, i.e. during the conceptual design stage. As showcased by current scheduling problems in the International Space Station (ISS) program and by the project history of its predecessor "Freedom" [14], more often than not, the success or failure of complex technological undertakings depends rather on the vagaries of the political environment than on the engineering competence of the designers involved [6]. Thus, mission elements to consider include not only flight hardware, crew selection and training, and direct operational issues, but also program risk management, integration of political issues, addressing cultural boundary conditions, etc.

These elements, as well as the actual technical subsystems of a planned station, are closely interrelated, thus creating a "wicked" problem [24]. To help obtain an optimized overall solution, a collaborative, iterative approach appears promising. Collaboration, in this context, refers to a process of "shared creation", where disciplinary experts interact "to create a shared understanding that none had previously possessed or could have come to on their own" [25]. For this task, the concept of systems architecture ([23], [19]) seems especially well suited.

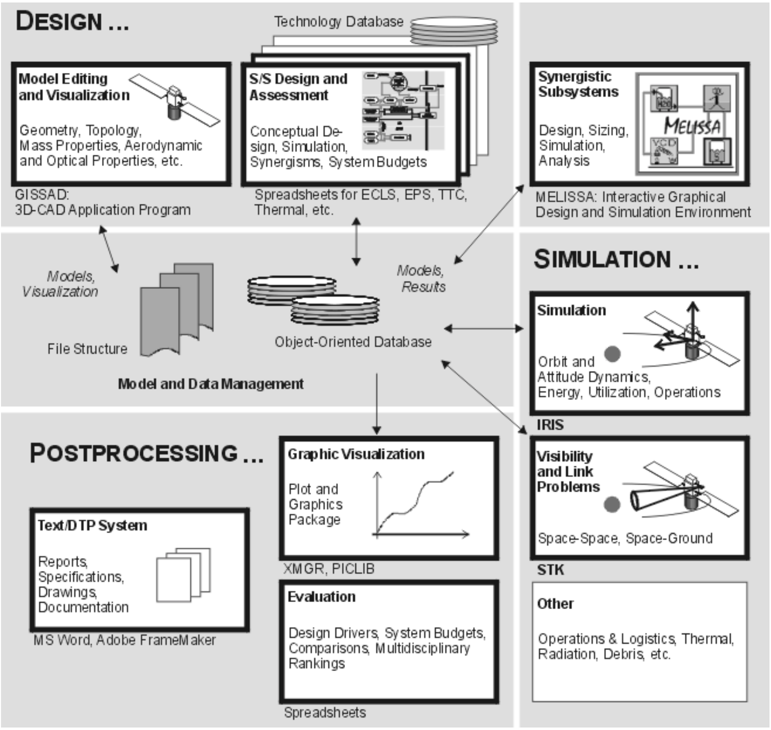

Figure 1. Space Station Design Workshop Methodology and Associated Tools [20]

The inclusion of technical boundary conditions is a prerequisite for successful human-oriented engineering [8]. Therefore, the approach described in this paper is based on an engineering methodology specifically created for the conceptual design of space stations [4]. In the following, this engineering methodology and elements from terrestrial architectural heritage are presented before the integrated human-centered habitat design approach is outlined and its application to a design example is demonstrated.

BASELINE ENGINEERING METHODOLOGY

The designer of complex space systems is faced with a set of challenges stemming in part from the general “wickedness” of such design problems, and also in part from the special environment of space and the boundary conditions which it imposes. These include [20]:

- “Fuzzy” problem formulation
- Strong interdependencies between system elements
- Adverse relationship between available information and consequences of conceptual design decisions
- Extreme environment
- Extreme loads
- Minimized weights
- Limited access after deployment

To help a design team deal with those challenges, a step-by-step systems engineering approach has been developed at the Institute of Space Systems that relies on a quasi-linear, iterative design flow and the use of supporting dedicated software tools [4].

Table 1. Space Station Design Workshop Methodology Steps

Step	Details
Define Objectives	A. Develop Broad Objectives B. Develop a Preliminary List of Requirements and Constraints
Characterize the System	C. Develop Alternative System Concepts D. Characterize System Elements
Evaluate the System	E. Prepare System Budgets F. Evaluate Mission Utility G. Select System Baseline
Define Requirements	H. Define System Requirements I. Allocate Requirements to System Elements

Table 1 summarizes the design steps; Figure 1 gives an overview of the associated software tools. The methodology specifically addresses the following issues:

- attitude and orbit stability and performance assessment
- life support system analysis
- power and thermal subsystems sizing
- determination of resupply requirements
- determination of microgravity quality
- assessment of synergistic linkages between subsystems
- launch, assembly and utilization issues

This approach enables a team of design engineers (or even graduate-level engineering students) to conduct the conceptual design of a space station within one week, as demonstrated by the highly successful Space Station Design Workshops (SSDW) that have taken place over the past several years at the University of Stuttgart [26].

CONTRIBUTIONS OF ARCHITECTURE

Adding select elements from architectural practice to the engineering-centered methodology outlined above will improve the design process and thus its outcome ([1], [19]). As Rechtin [23] states:

> *"Architecting, the planning and building of structures, is as old as human societies and as modern as planning the exploration of the solar system. It arose in response to problems too complex to be solved by preestablished rules and procedures."*

The design and construction of space stations like ISS represents one of the most complex technological endeavors ever undertaken [16]. At the same time, a space station is an icon of the cultural significance of pushing the space frontier, a tangible expression of humankind's indomitable spirit. This calls for appropriate expression both in the static shape and in the operation of a space station. These issues are addressed by the proper inclusion of architecture into the design process: on one hand, by emphasizing the *architect's role* in the design process; on the other, by making use of *architectural tools of the trade* which have applications in space habitat design.

The systems architect directs and accompanies the designed system throughout its life cycle, from conception to development to construction to operation. That person keeps an eye on "reducing complexity and selecting workability", guiding the work of the design engineers tasked with the implementation of the selected workable design [23]. Preservation of the original designer's intent throughout the design process serves as a safeguard against requirements creep and increases design consistency and simplicity. An experienced design engineer with the appropriate mindset can fill this role as well as an architect who is equipped with a thorough understanding of engineering and an open mind to interdisciplinary cooperation.

Terrestrial architectural practice provides several useful methods that were incorporated into the interdisciplinary space station conceptual design approach presented in this paper. These are:

- Extensive use of hand sketches
- Emphasis on important details starting from the earliest design phase
- Deliberate development of alternative design solutions and their variations
- Optimization of creative potential of the designer or design team

Other elements that can be made use of include structured lists of construction materials [9], or the utilization of design experience gained from the construction of earth-based analogs [21].

HAND SKETCHES – Why use hand sketches instead of computerized drawings? There still is a place for manual sketches in conceptual design beyond the "back-of-the-envelope drawing" commonly associated with this issue.

Hand sketches are usually accomplished more quickly than similar computer-generated drawings. When sketching, exploring solutions and reflecting on the task are in the foreground, as opposed to mere computer-aided documenting of preconceived concepts.

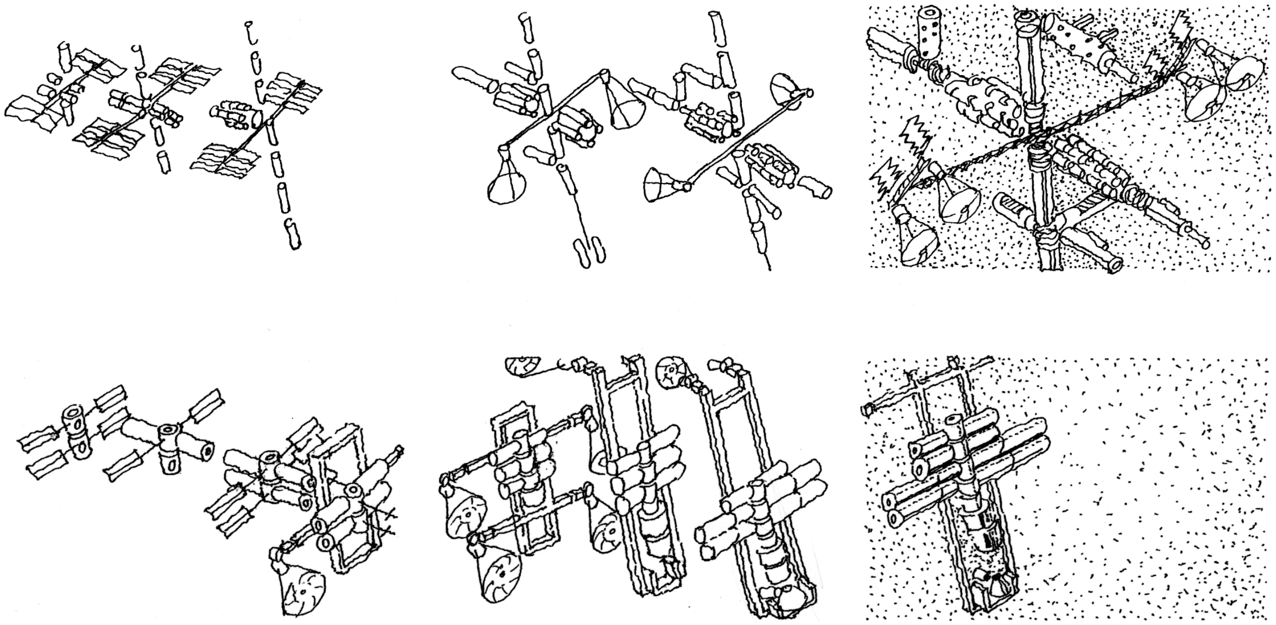

Figure 2. Configuration Sketches – Communication and Creativity Tool as well as Documentation Aid

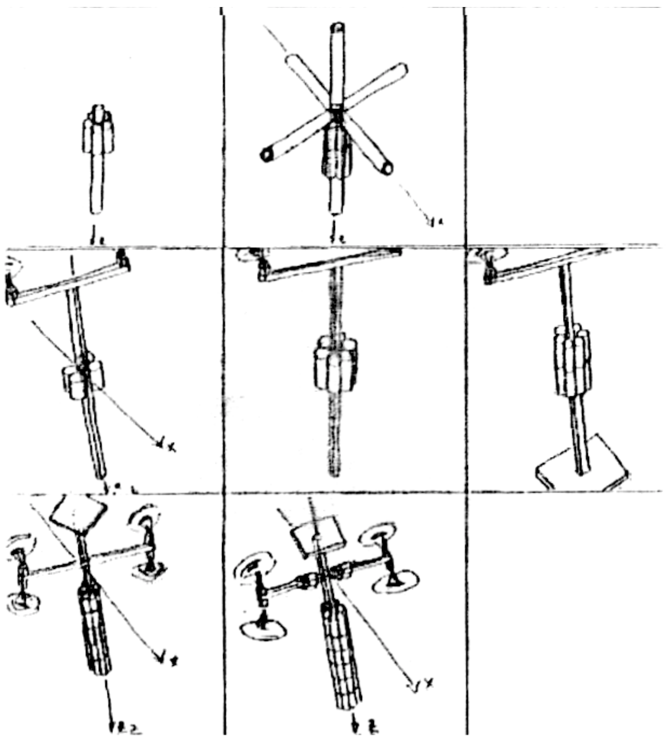

Figure 3. Development/Documentation of Growth Phase Variants [18]

Sketches as visualized language communicate and document the designer's/drawer's intent in a condensed, concrete form. On the other hand, unlike the streamlined, interchangeable lines of a CAD drawing, their appearance often fosters the creative process through ambiguity: the same sketch appears different if examined with increased knowledge, or by different persons, or even at a different time (Figure 2), as long as the viewer has sufficient practice [18]. Ambiguity in a design sketch corresponds to ambiguous design requirements and relates to the varying uses and configurations of a space station during its life cycle.

At the same time, hand sketches provide a constant reality check for the designer ("only what can be sketched can be built", [29]), thus guiding the thought process towards feasibility.

IMPORTANT DETAILS – Including the detailed design of certain elements in the conceptual design phase of the overall system stands in contrast to the traditional top-down engineering approach. Nevertheless, key details sometimes determine the overall system layout, or affect project feasibility. To provide an example, the EVA system (suit/airlock) represents just such a key detail for a space station project with an EVA-intensive assembly phase [12].

Pre-designing significant details offers guidance to designers in subsequent steps, thus preserving the system architect's intent and focus. Looking at important details early in the design process also satisfies the inquisitive nature of human thinking, promoting the creative flow.

ALTERNATIVES – Especially during the early stages of conceptual design, generation of a number of alternative system designs that are feasible (and able to be analyzed) is vital in order to increase the chances of finding a viable solution that will satisfy all requirements and constraints. The development of variants is therefore forced even if one solution seems to be workable from the beginning (cf. Figure 3) [18]. The systematic search for configurational alternatives can be aided e.g. by geometric typologies [11].

After careful analysis, the decision among equally rated alternatives is often made as a personal decision of the architect, weighing numerical analysis results against experience and qualitative results. Alternatives that are not selected at this stage are nevertheless taken seriously and kept for future reference.

OPTIMIZING CREATIVITY – Generating workable alternatives, communicating with sketches, as well as identifying and designing important details all require a large amount of creativity on the part of the architect or design team. To optimize the creative process, a maximum amount of information is made available at the beginning of the conceptual design phase through thorough background research [13].

This research, and the thorough comprehension of the gathered knowledge, is the prerequisite for the successful creation of alternatives and variants. Few things endanger the creative process more than the precocious "brilliant idea" that becomes a favorite before the task and the background information are fully analyzed and understood. Such ideas will linger in everyone's mind, biasing incoming new information (through the forming of patterns of perception, [13]), pushing towards their realization, and discounting all alternatives.

INTEGRATION: HUMAN-CENTERED HABITAT DESIGN

Just as the design result has to accommodate the capabilities and limitations of the human crew, the design process must also be adapted to the limitations and capabilities of the designers. Since, historically speaking, terrestrial architects have gathered significantly more design experience than have space station engineers, the inclusion of the time-honored elements of architectural practice outlined in the preceding section promises to result in an improved space station design process. The main elements of such a process, given below, address design flow, human-specific issues, and design team composition, supplying specific guidelines to the designer(s) in each of these areas.

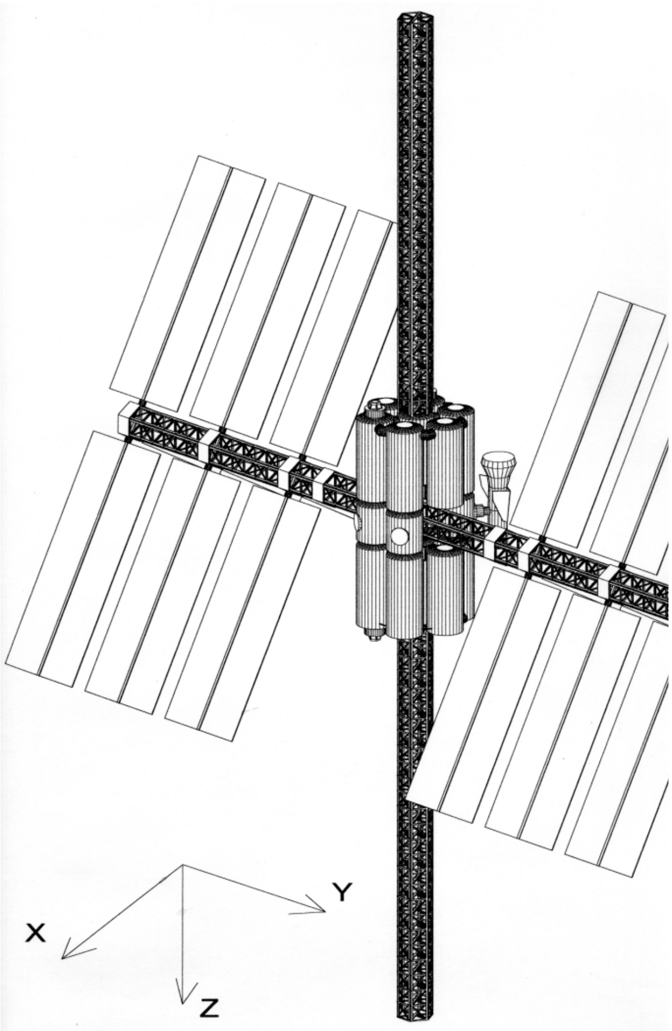

Figure 4. Design Example Station Configuration [15]

DESIGN FLOW – The improved methodology generally follows the design flow summarized in Table 1, but stays flexible by allowing for temporarily “jumping ahead” or iterating back if such deviations help the creative process or the understanding of the design problem. The workflow is further guided by the following principles:

- Design team members realize that the early phase of the design effort (task analysis, gathering and understanding background information, collecting ideas, generating multiple design alternatives) is crucial and should extend far into the design process
- Alternatives not selected are not discarded, but kept for future reference, as sources of ideas, or as a fallback option in case of changing requirements or design impasses
- Important details are identified early in the design process; they are developed as soon as relevant boundary conditions have sufficiently evolved; and from the beginning, they help to provide focus on and continuity for the designer’s intent
- Variants are created by applying task-derived rules to existing patterns, thus opening the path for new thoughts and new solutions

HUMAN-SPECIFIC ISSUES – The addressing of human-specific elements by the design team is emphasized. For each step, the designers are encouraged to adhere to the following conventions:

- The “human element”, i.e. the crew, is not treated as a subsystem among many, but is singled out as the overall design driver: the design objective is the creation of a habitat
- Human needs determine the types of modules to be used and their internal layout (“Archetypes”, [2]) as well as the dynamic linking of these modules to the overall habitat (“Choreography”, [2])

As a cautionary note, however, the design team should realize that the Human Factors (HF) contribution to human-rated space exploration missions should not be exaggerated. While it is certainly wise to optimize a mission with respect to crew efficiency and habitat comfort, history shows that expedition participants have frequently been able to withstand extreme levels of discomfort [27]. Fear of the “Human Factors Dragon” [30] and the resulting tendency to over-design for HF carries the risk of jeopardizing overall mission feasibility. As with subsystem issues, the integration of key requirements into the overall system concept is preferable to subsystem-specific local optimizations with limited scope.

DESIGN TEAM – The third central element is the composition of the design team and their mode of collaboration:

- The design team is comprised of members who see themselves as cooperation-oriented disciplinary experts instead of as isolated subsystem specialists and who are aware of – and can make use of – the nuts and bolts of creativity-fostering processes
- Design team members have different disciplinary backgrounds, but speak a common language; this suggests that they share joint design experience gained through participation in previous design projects or hands-on training workshops
- Design team members look for solutions based on their disciplinary experience, but their ideas are triggered by interdisciplinary interaction and exchange; they are aware of the design process also being a learning process [10]
- The use of hand sketches is encouraged for the communication and generation of ideas among design team members as well as for documentation purposes and as a constant reality check
- The design team sees itself as an agent and advocate of the customer, assuring fulfillment of customer needs – which might even differ from the written requirements – and interfacing with the builder/detailed designer of the system throughout the design process

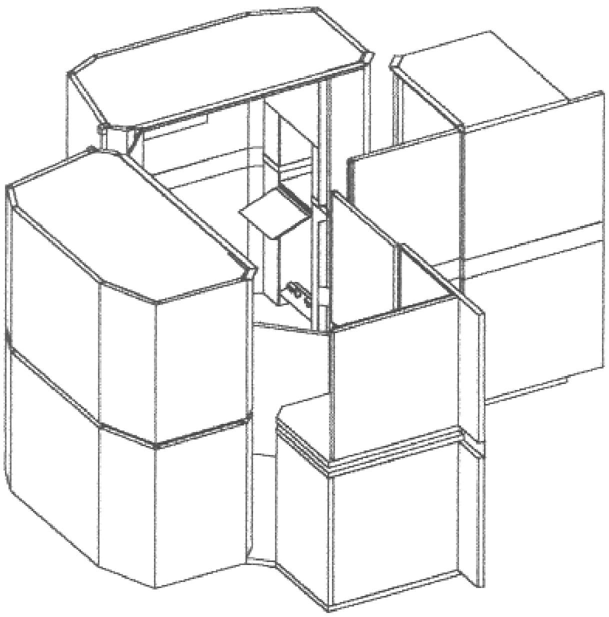

Figure 5. Significant Detail: Crew Quarters Design [15]

- Designers must be on the lookout for the usual hazards of requirements creep, fuzzy mission statements, departmental or disciplinary infighting, and marginal performers

APPLICATION: SPACE STATION DESIGN EXAMPLE

To develop and validate the design approach described above by applying it to “real problems in the real world” [10], a graduate-level interdisciplinary space station design project was started in 1998. In its first phase, the participating architecture and aerospace engineering students were tasked with conceptually designing a space station dedicated both to commercial utilization and to the preparation of human-rated exploration missions to Mars.

In accordance with the improved SSDW approach specified in the preceding section, the design process was executed and documented. Figure 3 shows some assembly sequence options that were analyzed. The three most promising alternative configurations were modeled using the SSDW software, and AOCS simulations were performed to determine attitude stability and resupply requirements [17]. The optimum configuration was then developed in greater detail [18].

The second phase of the design project started with a new design team tasked to optimize the internal configuration of the station concept developed during phase one. The emphasis was on human-centered design, from module allocation and layout to interior translation paths. The second phase also permitted to perform another iteration on the overall configuration, leading to mass savings (more compact modules) and reduced technology development risk (the solar dynamic EPS was replaced by a photovoltaic EPS). Figure 4 depicts the computer model of the final configuration after design phase two. Documentation included detailed level-by-level cross-sections of the interior station configuration (similar to floor plans of terrestrial buildings) and renewed AOCS and assembly sequence simulations based on the modified configuration [15].

In concurrence with the methodology, key details were also conceptualized during the second phase. This includes innovative crew quarters, a human-powered-centrifuge/exercise module, and a combination table/seat rack.

The proposed crew quarters provide ample living and working space for crewmembers, while maintaining rack standardization and full rack exchangeability. Each crew quarter consists of two connected full racks (ISPRs, as used on the International Space Station, [20]), and two connected rack halves, oriented at a 90° angle. When in use, the rack fronts are swiveled outwards into the module corridor and connected there, thus increasing the habitable space for each crewmember to about 7 m^3. Figure 5 shows an isometric view of two such crew quarters (with the rack-front divider walls between the two quarters and the end covers removed for clarity). Figure 6 is the corresponding cross-section. The remaining quarter-circle-shaped area of the module corridor still provides ample translation space. When the rack walls are not deployed into the corridor, the full racks can nevertheless be used as makeshift sleeping quarters and the rack halves for storage.

Detailed design of such crew quarters, including the manufacturing of a full-scale mockup and subsequent microgravity testing, is the subject of an ongoing design project.

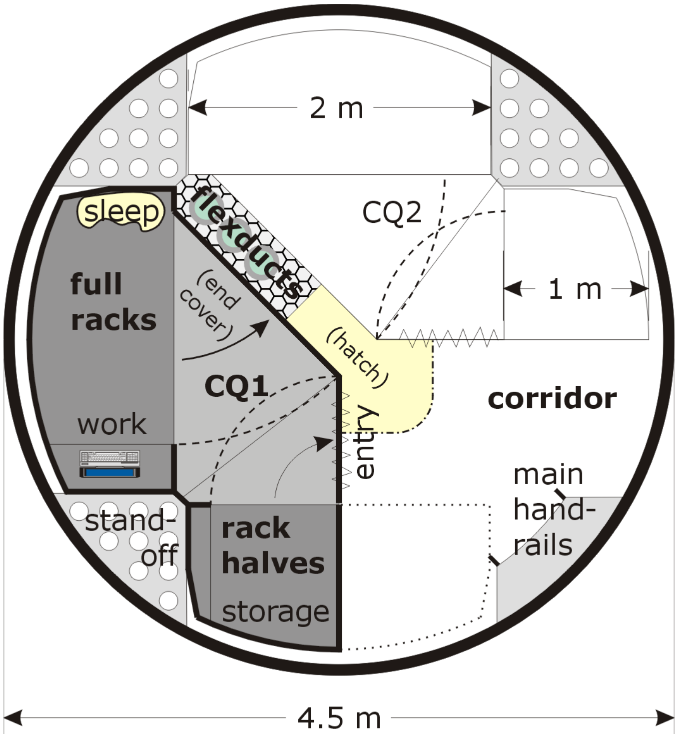

Figure 6. Crew Quarters (CQ) Cross-Section

CONCLUSION

An interdisciplinary process for the conceptual design of long-duration, human-rated space missions has been developed, incorporating a human-centered, habitat-oriented approach. It is based on an existing, validated systems engineering methodology and includes elements from the domain of terrestrial architecture. An interdisciplinary space station design project using this new process demonstrated the validity of the chosen approach. Further development is underway to improve modeling, simulation and visualization capabilities.

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ACRONYMS

AOCS	Attitude and Orbit Control System
CAD	Computer-Aided Design
CQ	Crew Quarters
EPS	Electrical Power Supply System
EVA	Extravehicular Activity
HF	Human Factors
ISPR	International Standard Payload Rack
ISS	International Space Station
MELISSA	Modular Environment for Linked Subsystems Simulation and Analysis
SSDW	Space Station Design Workshop