RETROFITTING THE INTERNATIONAL SPACE STATION (ISS)

Susan M. Fairburn
Fibre Design Inc., suefibre3d@yahoo.com

INTRODUCTION

Crew quarters (CQ) design was key to the habitability design of Skylab, with a specific goal of providing a private space for each crewmember, who might spend 6-8 hours a day there. Despite the privacy afforded by a designated place for each crewmember, Skylab crews reported poor sleep due to noise, light leaks, or disturbances by fellow crewmembers. Adams (1998) noted that Skylab lacked attachment points for relocating sleep restraints, thereby effectively precluding crewmembers from sleeping elsewhere. Generally speaking, Skylab's interior outfitting was not designed for modularity or reconfigurability. In contrast, one of the principal design features of the International Space Station (ISS) is the basic structure of the modules and the rack volumes they accommodate, the International Standard Payload Rack (ISPR). The ISPR is intended to allow interchangeability and reconfiguration.

Feedback from expedition crews who have lived onboard the ISS include requests for an improved living environment. Designers can improve the living environment, in part, by learning from the experiences of these crews. By developing solutions that can be retrofitted to the existing basic structures, designers could offer an environment that enriches a crewmember's experience.

Crew feedback has cited flexibility of use as a desirable feature during long-duration missions. For such missions, flexibility allows objects or environments to be used in different ways, requiring fewer amenities and less room to house those amenities, thereby reducing transportation demands and costs.

Flexibility offers numerous advantages for space applications where the living volume is limited and delivery and maintenance costs are major concerns. A mounting structure and "kit of parts" system could offer flexibility of use, a benefit for crewmembers who desire visual stimulation and variety in the space station environment. Moreover, this approach is durable; any part would be able to be detached and updated, improved, or replaced.

This chapter presents a design solution for a flexible CQ system. The process behind the solution involved a series of self-directed empirical exercises that provided insight and spurred concept generation. Subsequently, a review of relevant ISS specifications served to guide design development. The resulting design is compatible with the basic elements of existing CQ equipment, offers adaptability over time using a proposed "kit of parts," and thus an interior strategy that allows crewmembers to tailor the layout and use of their private environment at any time.

BACKGROUND

The primary objective of the ISS is to provide a manned outpost for scientific research in a reduced-gravity environment. As terrestrial creatures, we are continually exposed to the gravitational field of the earth. Gravity shapes our perceptions and expectations of how we interact with our environment. Orbital microgravity is an environment that brings both opportunities and restrictions. We are able to anticipate the effects of weight from gravity and adjust accordingly - weightlessness must lead therefore to adjustment and re-orientation.

Figure 1: NASA Artist conception of the ISS in its April 2002 configuration.

ISS Status and Utilization

Core Complete: Significant cost overruns and increasing budgetary constraints necessitated a reduced ISS configuration referred to as the "ISS Core" (Figure 1). The reduced station could only provide formal CQ accommodations for a permanent crew size of three instead of the originally planned six. Basic maintenance and operation of the ISS with a crew of three leaves very limited time for scientific research.

Assembly Complete: In the original plan, the final module to complete the ISS assembly would be the Habitation module, accommodating four private CQ and dedicated to crew needs like hygiene, meal preparation, medical conferencing, personal stowage, privacy, and socialization.

Interim Stages: Interim plans would accommodate a crew of six by means of temporary CQ. The Temporary Early Sleep System (TeSS) is an example of an interim solution for a personal living volume to be located in existing modules and nodes, such as Zvezda, Node 2 and Node 3 (NASAexplores, 2001). This interim accommodation solution approximates the baseline ISS goals at reduced cost. TeSS offers a crewmember a personal living volume, but not the same degree of privacy or crew conveniences as CQ in designated rack volumes in a habitation module. Thus TeSS serves on a temporary basis, as ISS is in a makeshift situation with crew accommodations having a lower mission priority than originally planned.

Mission duration and habitability

Living in the ISS means existing in a confined, limited volume, in close proximity to fellow crewmembers, with no chance to "get away." Individual responsibilities are significant and stress levels can be high. Privacy is a necessity. In the closed quarters of space habitats, individuals need to have their own place in order to rest and relax. The closer one is to others, and the more time one spends in close proximity, the greater the need for a means to retreat.

Clearwater (1985) cites research and experiences derived from analogous environments, including prior space stations, as supporting a holistic approach that takes into consideration various issues - for example psychological, social, and physical - in the design of the environment. Providing crewmembers with places of their own to personalize and use as they choose would recognize the psychosocial significance of having personal space. More importantly, the provision of choice recognizes that some crewmembers may prefer a personal living volume, while others may opt for a sleep enclosure such as TeSS that can be secured in any available locale.

One of the key challenges designing the interior configuration of living space in such a limited volume is to provide a sense of spaciousness while offering enough flexibility for adaptation to different uses, and users, over time. A good design would therefore take into account crew interaction, privacy, proximity, lighting, sight lines, circulation, and crew activities and schedules. These issues and others are relevant to achieving a habitable interior, i.e., an interior that promotes productivity, well being, and desirable occupant behaviors (Bedini and Perino, 1999).

Addressing CQ habitability through design

One plausible way to improve habitability aboard the standard pressure modules of the ISS is by retrofitting the existing rack structure with a shell that supports adaptation and evolution over time. This approach would offer an adaptable enclosure that could be outfitted for various crew needs, the most likely example of which could be for crew quarters.

To retrofit is to provide an existing machine or structure in use - such as a jet, a computer, or a space station - with parts, devices, or equipment that did not exist, or was not available, at the time of the original manufacture.

The design of the ISS is based on pressurized modules of similar dimensions, linked together by smaller node elements. The ISS must accommodate growth and the possibility of reconfiguration due to the anticipated length of time to construct the station and its project lifetime. Retrofitting is likely at various stages of the ISS' lifecycle, as technological advances continue to improve station features and capabilities. Retrofitting is also a suitable approach to CQ design and outfitting. The approach supposes a baseline structure that allows for evolution and adaptation over time, thus may be termed "time-based modularity."

Howe (2002) defines a kit-of-parts design by noting that it is based on the organization of individual parts and materials into "assemblies of standard, easy-to-manufacture components, sized for convenient handling or according to shipping constraints..." One of the strongest advantages of the kit-of-parts design and construction approach is that it not only "...achieves flexibility in assembly and efficiency in manufacture, but also by definition requires a capacity for demountability, disassembly, and reuse," (Howe, Ishii and Yoshida, 1999). Adopting a kit-of-parts philosophy adds flexibility to a building or artifact by providing elements that allow for arrangement and rearrangement.

The ISS is itself a kit-of-parts consisting of several components: modules, nodes, truss segments, solar arrays, and thermal radiators (Messerschmid and Bertrand, 1999). While some parts of the ISS may not be intended for disassembly and reuse, the basis of the ISS truss and standardized pressure modules system is consistent with kit-of-parts design.

Flexibility is a common attribute in terrestrial furnishings, with examples including objects and environments that offer multiple options for arrangement and flexibility in function. Flexibility can be achieved through a group of objects that can be configured to achieve different functions; by a system that supports a family of objects, each possessing a unique function; or by arriving at a reduced collection of elements whose functions are fused.

Gianantonio Mari, an Italian designer, conceived of a modular environment made up of a dynamically organized space that would house modular and combinable furnishing units (Ambasz, 1972). The system was based on a grill support structure that permitted horizontal or vertical extensions via a support structure and a collection of modular interior equipment (Figure 2). Design of the interior elements addressed the various functional requirements (e.g., containment, support, separation) while allowing for personal expression of use. Mari defined use through a study of rituals and ceremonies, in five major categories: privacy, sleeping, dining, leisure and sensory.

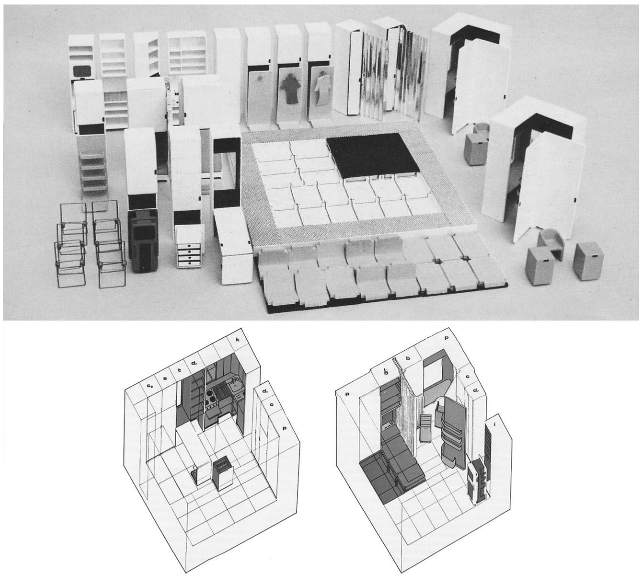

Figure 2: G. Mari's "Modular Equipment for New Domestic Environments."

More recently, Rashid's Surfacescape (2001) is a furniture system that reduces clutter by fusing functions into four 'seating' units: chaise/seat, multi-level seat, carpet/seat and booth/couch. A floor plan as structure, in combination with the four 'seating' units, permits multiple arrangements, resulting in a system that is modular in function.

Extended space missions necessitate a flexible environment with outfitting that can be reconfigured for cleaning and maintenance, and to accommodate changing crew composition, preferences and activities. This approach is consistent with the ISPR standard and hardware which allows exchanging racks (equipment, CQ, etc.).

NASA defines an ISS CQ rack as follows:

"The crew quarter rack shall provide each individual crewmember with private space isolated from external light and sound to sleep, don and doff clothing, read, write, perform recreational activities, and for personal/private and medical consultations. The crew quarter shall also provide limited storage for personal items, clothing, and computer accessories. Interface locations shall be provided for handhold, mobility aids, and restraints." (NASA, 1999)

HUMANIZING SPACE

The author prepared the following statement, at the outset of the project, to serve as a guiding principle throughout the design process.

"In your private crew quarter, at any time, you may need: light, control of body position, a work surface, a place to put things, ventilation, privacy and darkness - so that you can sleep, display photos/treasures, store clean/dirty clothes, stow rubbish - you need a place to rest, to relax, to read or to listen to music, to meditate, to do personal work, to communicate, or to just be."

Providing crew members with environments that can accommodate their personal needs and preferences is challenging given the limited volume, payload restrictions, safety specifications, and the objective of maximizing acceptability of the environment for a heterogeneous group of users.

Design Process

Insight into the issues and challenges associated with designing a personal CQ was obtained in numerous ways including literature review and a creative process of idea generation. A series of three, self-directed empirical exercises explored the issues of confinement, simulated weightlessness, and personal space as well as the personalization of a living volume. While the exercises provided valuable insight into some of the issues discussed in human space exploration literature, ISS specifications provided tangible realities to guide the final design.

Figure 3 illustrates a concept based on breaking the CQ envelope into discrete surfaces: a faceted form as an expression of the multifunctional nature of the constrained personal living volume. The concept evolved from simulated weightlessness underwater, where achieving a position and orienting oneself was viewed as three-dimensional interaction with a multi-planed sphere.

The design process included the construction of a full-scale ISS rack volume. The volume served as a basic shell that could be entered to promote a better understanding of the limited space. It also allowed for the addition and arrangement of interior elements to aid in the exploration and development of the CQ interior concept.

To achieve a satisfactory solution, some key assumptions were made about how the CQ would interface with the existing ISS module structure and equipment:

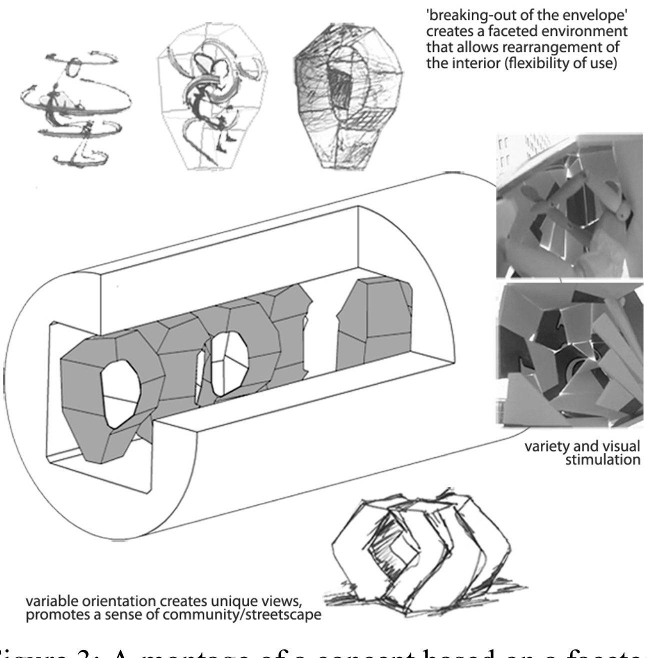

Figure 3: A montage of a concept based on a faceted, multi-orientation volume.

1. The CQ would be attached to the Habitation Module and secured in place using the existing rack hardware and seat-track frame.
2. Access to the pressure shell of the module, in the event of damage, and to the standoffs for maintenance procedures would be achieved through the removal of the whole CQ.

Proposed Design - Shell

The design evolved from the premise that the interior layout should be dynamic; that is, it should be in a continual state of transformation determined by a crewmember's preferences and patterns of use. At this point, one could envision the form that such a proposal would take within the context of the ISS rack (Figure 4): a shell with an integrated array of attachment points to support the arrangement and rearrangement of a family of functional elements.

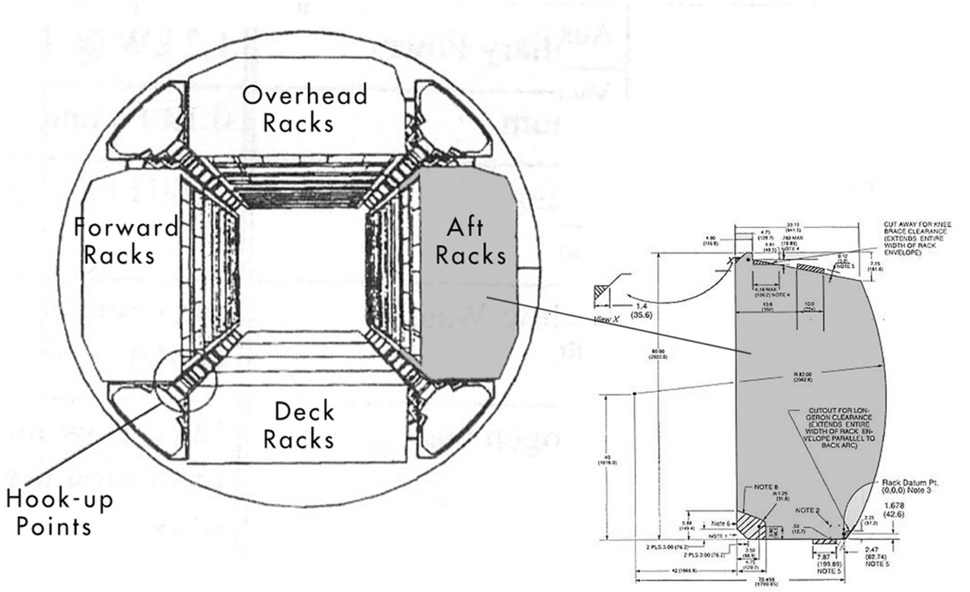

Figure 4: ISS rack structure (ISPR).

As shown in Figure 5 below, the shell houses the CQ activities. The design is of an asymmetrical form, offering crewmembers visual variety, stimulation, and relief from the symmetrical, linear environment of the space station. The exterior is made up of three walls, a floor and ceiling, as well as a front bumpout and access section. When assembled, the tapered form provides a variety of surfaces for tailoring the arrangement of interior features.

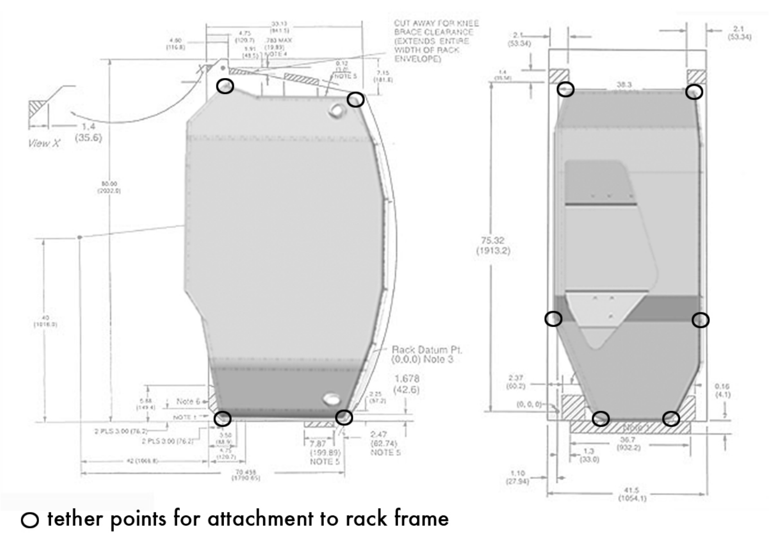

Figure 5: CQ shell shown with tether points for securing the shell to the rack frame.

An environment that supports a crewmember's adaptation is an important consideration in habitability. Providing an interior that facilitates movement and control of position is an exciting challenge open to designers. The second of the three self-directed empirical exercises, the underwater sessions, provided inspiration for the design. The essence of the exercise was the experience of the natural state of the human body and loose objects in a simulated weightless environment. The impression generated by the experience was that in weightlessness, the natural state is motion and there is an absence of rest, whereas in a gravity-weight environment, the natural state is rest.

Designing for movement in space: control versus freedom

Positioning oneself in space may be active or passive. For the purpose of this project, active restraint is defined as control of body position requiring the expense of energy to engage surfaces and/or edges. An example of active restraint is an individual reaching for something by hooking a toe under a surface and grasping a hold (two point restraint). Bracing between surfaces is also active restraint. Passive restraint allows an individual to maintain a position without requiring expenditure of energy. Examples of passive restraint include the user being in a sleep restraint, or being "wedged" between objects or surfaces.

While living in space, crewmembers adapt to weightlessness, learning how to move about the station and position themselves to perform tasks. A crewmember may choose to retrieve an object in the CQ by bracing between surfaces, an approach that requires a combination of planes that the individual is able to comfortably span. Bracing is commonly used within the ISS.

The faceted exterior shell facilitates positioning in the CQ by offering a crewmember a choice of surfaces, with varying dimensions, angles and shapes, for control of body position through bracing. The CQ shell also provides the frame and housing for a family of interior elements: panels and holds.

Kit-of-parts design philosophy supports the use of a standardized mode of attachment to maximize the possibilities for arrangement of parts and utilization of the system. However, the number and distribution of attachment sites is an important design consideration for ensuring the system meets its functional requirements while enriching the personal living environment.

The array of attachment sites in the CQ shell was defined by the system interface. It was apparent that the array needed to maintain a balance between flexibility, economy, usability and aesthetics.

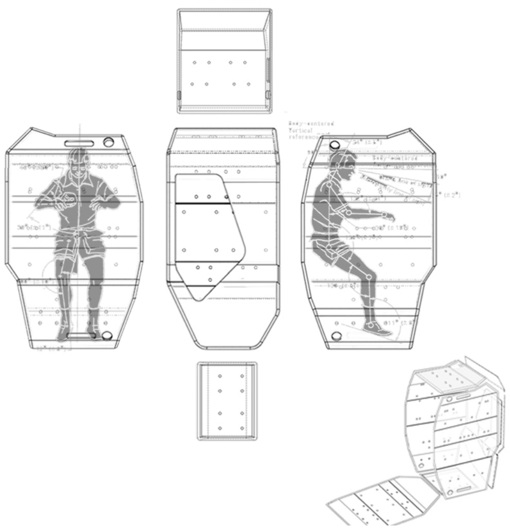

Figure 6: CQ shell surfaces shown with the interior array of attachment points and in CQ assembly. Figures of a crewmember in neutral body position, shown in two side views, convey scale and proportion.

Although a reduced gravity environment offers opportunity for three-dimensional usability, it was not necessary to provide complete coverage of the interior surface. Some aspects of the CQ, such as the lower corners, are awkward to access and therefore serve designated operational purposes (e.g. ventilation units, power and data intakes/outlets).

While a distribution of attachment sites offered broad functionality and flexibility for the user, it was important to consider the possible range of user dimensions so the array would be practical for all crewmembers.

Attachment points were based on the ergonomics of positioning and mobility for the various types of activities that take place within a personal CQ. This process took into account reach envelopes and the user range specified by

NASA: 5th percentile Japanese Female to 95th percentile American Male. An example of this user size range for the dimension of stature would be from 148.9 cm to 190.1 cm, respectively, or a 41.2 cm spread (NASA, 1995). The dimensional indicators used included stature, biacromial and trochanteric height, and hip/chest breadth (Figure 7).

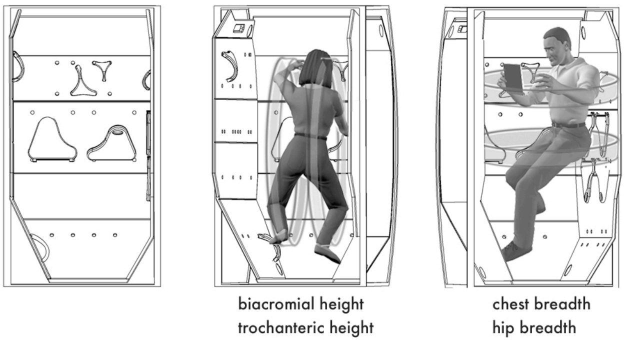

Figure 7: An anthropometric array showing attachment points and a distribution of panels and holds to support and position the body.

While the issues of reach envelopes and user dimensions were considered, development of the array and kit-of-parts also evolved from a study into patterns of use. Figure 8 illustrates the patterns of use for two different hypothetical users referred to as "the organizer" and "the free-formist." This evaluation was done during the development of the system, so the images are based on an early version of the interior elements.

Figure 8: Patterns of use during a 24-hour period, showing diversity of layout for two different crewmembers: "the organizer" (top) and "the free-formist" (center and bottom).

Proposed Design - Kit-of-Parts

An integral part of the process was to evaluate the appropriateness of different combinations of interior elements. Consideration of the types of activities, and the position of the user when performing those activities, allowed for an exploration of opportunities for fusing functions. For example, while reading, an individual may prefer some way of controlling body position. To perform a personal work activity, such as writing a letter, an individual requires a hard surface. Figure 9 illustrates various uses for the panel form, shown for different tasks and two users of differing dimensions.

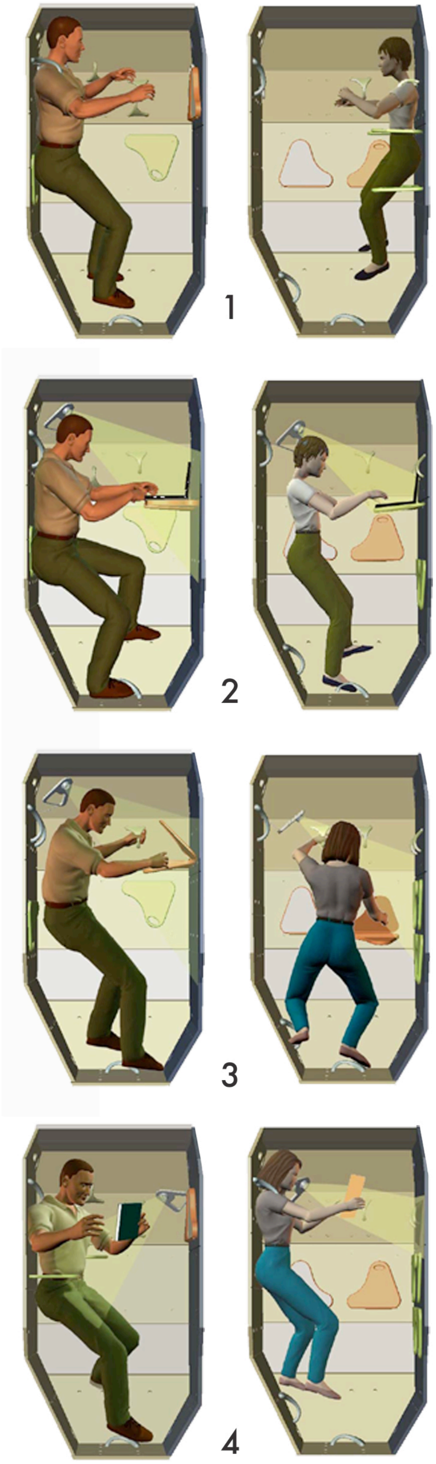

Figure 9: CQ layouts showing interior functions for a variety of crewmember living activities: 1:sleep, 2:personal work, 3:store/retrieve, and 4:rest/read.

The combination of desirable features presented an opportunity to design an element that would offer control of body position while also providing a surface for writing or displaying images, such as photographs. Fusing the functions into a panel element that provides edges for positioning and a surface for working was considered an appropriate way to promote the flexibility and usability of the system as a whole.

Design development led to a variety of panel types, as shown in Figures 10a and 10b. The decision was informed by the need to address a range of functional requirements, answered through a variety of edge contours, thickness and surfaces. Two main types of panels were designed: storage panels and working panels; both types hinged. The storage panels offered volume as their primary requirement, while the working panels provided surface and attachments. Although some functions could be fused, some functions required designated design features; such as clips for securing papers/artifacts, reveals for grasping and lodging items, and openings for containing objects. The end result was four panel components.

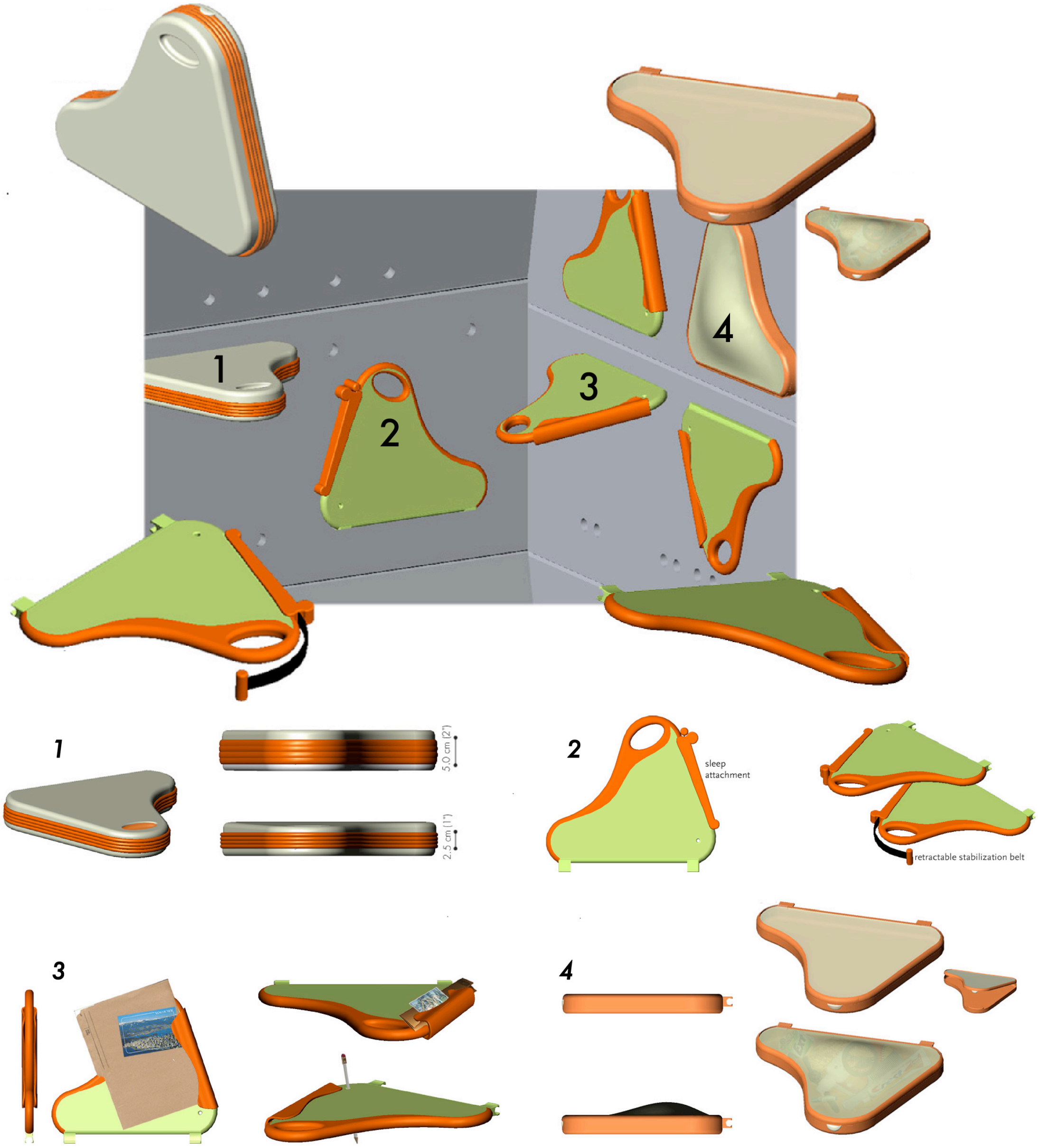

Figure 10a, 10b: Panel components shown in CQ arrangement (a) and in context (b): 1: storage panel with expandable bellows; 2: work panel with retractable sleep attachment; 3: work panel with clip/artifact attachment; and, 4: storage panel with transparency.

Panels are moved by the crewmember, offering the means for storage, work surface, and body position. All of the panels rely on a common mode of attachment. A hinge was chosen to provide dynamic attachment, also serving as a grasping point (Figure 11). The hinge and panel combination allowed for the creation of intersecting planes in the CQ environment.

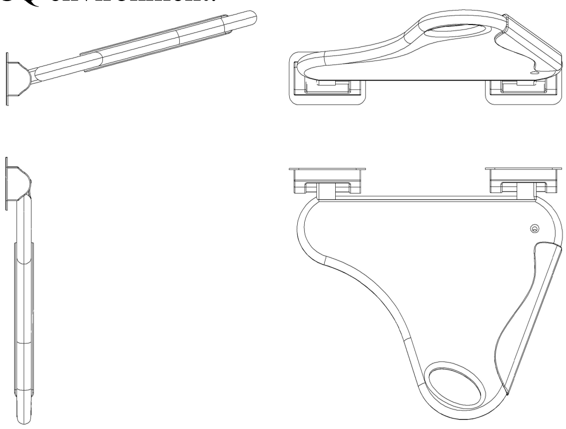

Figure 11: Work panel shown with hinge attachment (left to right: side and front view).

The kit-of-parts was completed by the addition of a 'hold' element, which complemented the panels. The 'hold' was developed when the evaluation process revealed that the panel element alone did not fully satisfy the functional requirements. Figure 12 illustrates two sizes of holds designed to offer static hook/grasp points that facilitate control of body position and motion. The holds offered temporary storage, such as hooks on a bathroom door, with their various arcs accommodating a range of object shapes and sizes, using one hold or wedging an object between two or more holds.

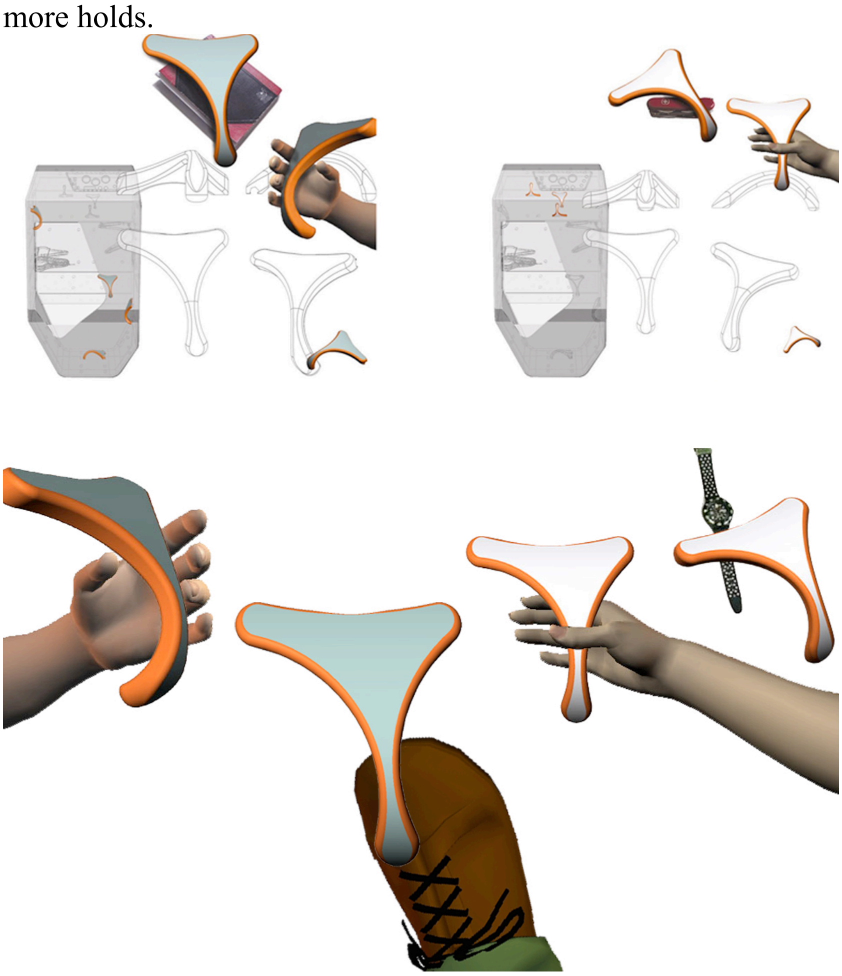

Figure 12: Close-up view of the two sizes of holds showing grasp, hook, and quick storage/display options.

The System in Use

The kit-of-parts CQ system presented in this chapter is based on panel and hold components (Figure 13). A light is included in the outfitting elements, but it does not follow the standard connection and is therefore not formally included in the kit-of-parts. The kit can be used in various combinations to meet functional requirements, while allowing a crewmember to personalize use of the living environment.

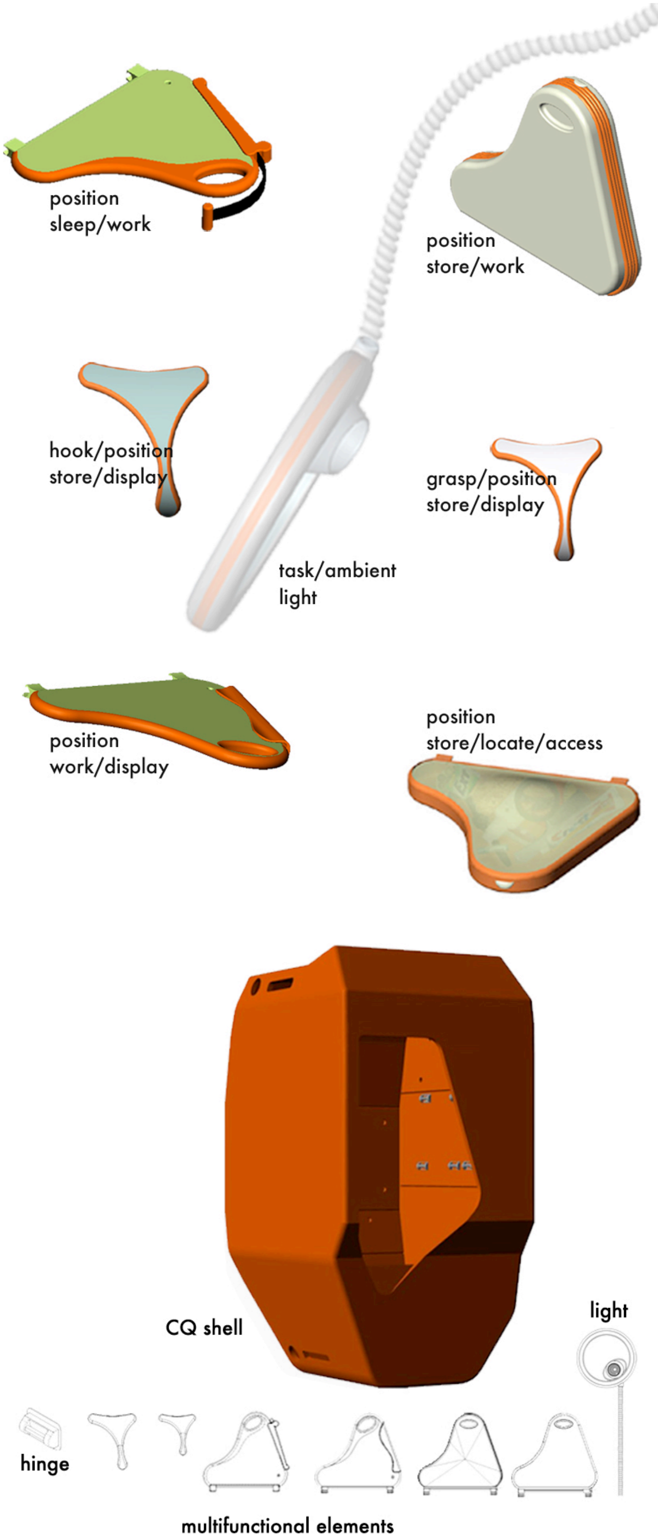

Figure 13: The kit of parts: CQ; hinge attachment; four panel types; two hold sizes; and a non-kit-of-parts element, a positional task/ambient light.

Figure 14 illustrates the system in stages. Assembly begins with the deployable shell, whose wall sections are sized for convenient breakdown, packaging, and transport. When in orbit, the walls of the shell slot together for assembly, with the completed enclosure attached to the rack hardware and secured in place. The shell would be outfitted with the standard, embedded hinge connections prior to transport. In keeping with kit-of-parts theory, once a standard connection is used, the possibilities for variations in form, scale, appearance, and the numbers of parts installed, is limitless.

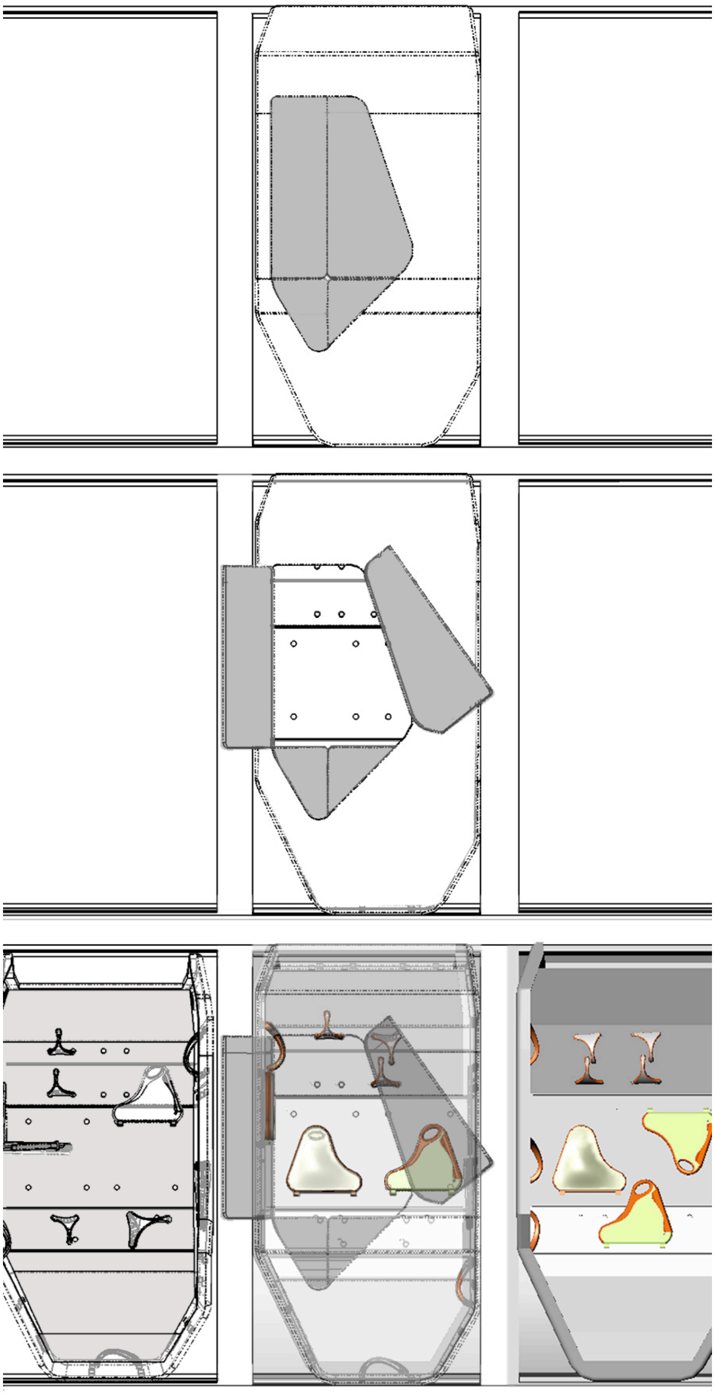

Figure 14: CQ System shown in stages of outfitting: (top) the shell in the rack volume; (middle) CQ shown with doors open but without parts, and (bottom) various kit-of-parts combinations.

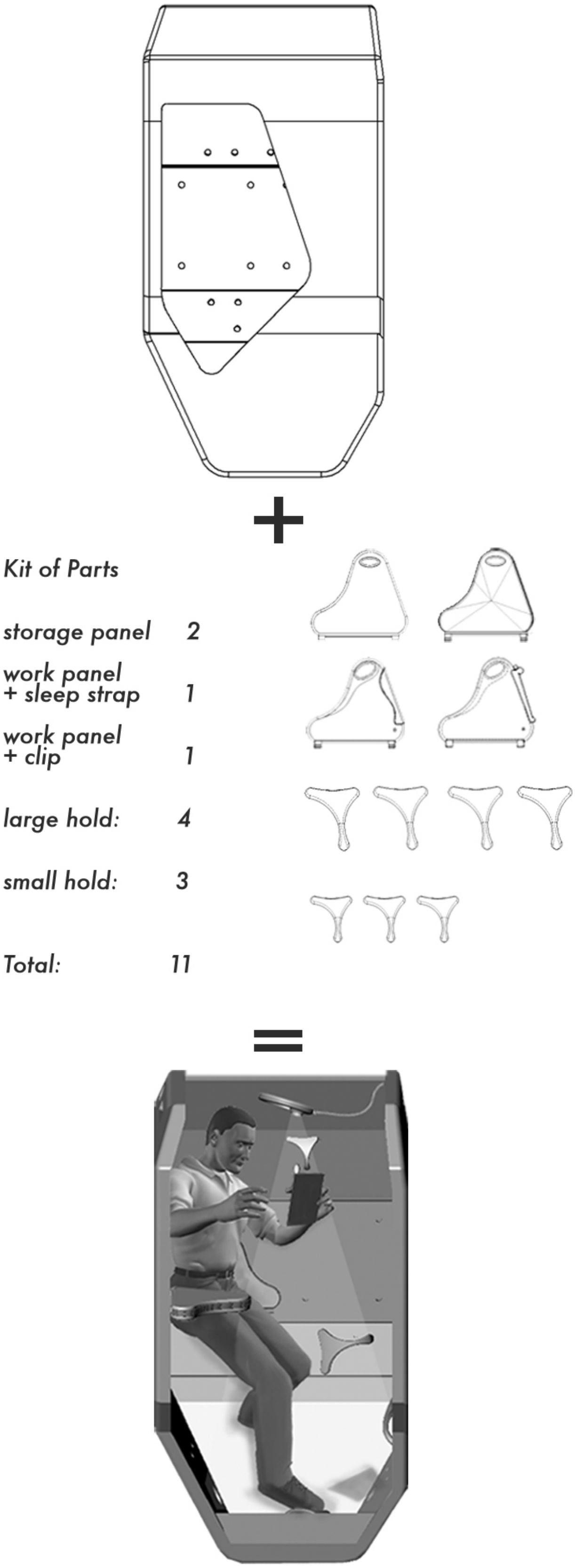

Figure 15: CQ System Overview #1 - A crewmember is shown in an active reading position, bracing between the lower surfaces of the CQ shell. A list of parts shows the combination for this CQ arrangement.

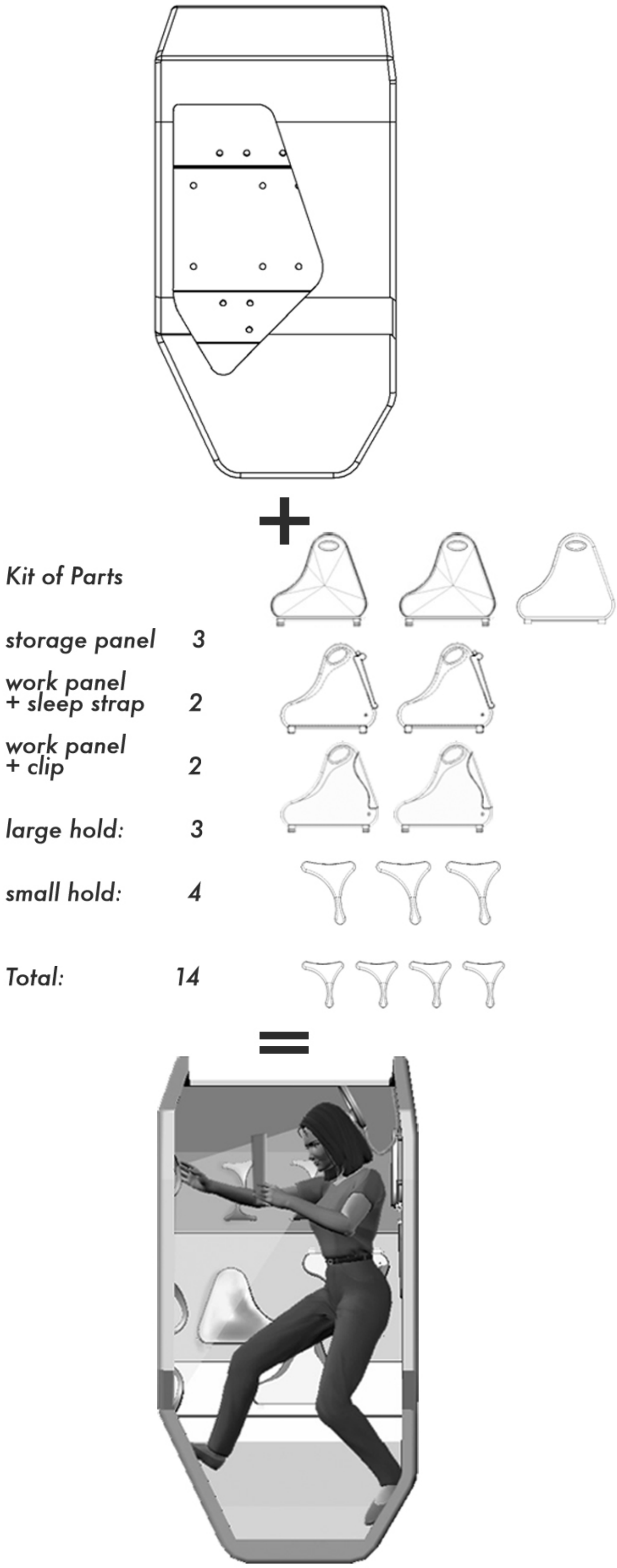

Figure 16: CQ System Overview #2 - A crewmember is shown reading in a passive position, wedged in the corner. A list of parts shows the combination for this CQ arrangement. Other applications

The proposed system - a shell and "kit of parts" - was developed for one use: a CQ. Yet it is plausible the same approach could also be utilized for other ISS habitability purposes, e.g., sick-bay/private medical or psychological consultation, library, workshop/studio, music booth, on-line education room, movie screening booth.

DISCUSSION

Is it too late to improve ISS habitability through design while the station is in a limited-growth condition? The design system proposed here offers a viable response. The combination of holds and panels for control of position that is flexible, easy to use, fun, intuitive, visually minimalist, and non-restrictive. Arrangements can offer both passive and active restraint depending on individual preference or the activity. Conversely, an arrangement designated for non crew-quarter use can accommodate different users while it serves the specified purpose. The attachment array is informed by the contributing factors of the altered microgravity anthropometry, reach envelope, and a balance between flexibility of use, economy of parts, and aesthetics. The design is compatible with the ISS architecture and basic elements of the existing CQ equipment, thereby allowing evolution and adaptation over time, and with use.

REFERENCES

Adams, C.M. (1998). Four Legs in the Morning: Issues in Crew-Quarter Design for Long-Duration Space Facilities. Paper 981794. Proceedings of the 28th International Conference on Environmental Systems (ICES1998), Danvers, Massachusetts, Society of Automotive Engineers.

Ambasz, E. (ed.). (1972) Italy: The New Domestic Landscape: Achievements and Problems of Italian Design. Museum of Modern Art, New York, in collaboration with Centro Di, Florence, p. 268-275.

Bedini, D. and M. Perino (1999) Section 6.3 - Space Architecture for Human Systems, in Keys to Space: An interdisciplinary approach to space studies. International Space University. McGraw Hill, Boston, p. 6.17

Clearwater, Y (1985). A Human Place in Outer Space. Psychology Today, July 1985, 34-43.

Howe, A.S. (personal communication, May 20, 2002).

Howe, A.S., Ishii, I., & Yoshida, T. (1999). Kit-of-parts: A review of object-oriented construction techniques. Proceedings of the International Symposium on Automation and Robotics in Construction (ISARC 16), Madrid, Spain.

NASA (1999). End Item Specification (EIS) for Crew Quarters, Revision NC February 17, 1999, International Space Station Program SSP 50356, Section 3.1, p.8, NASA Johnson Space Center, Houston, Texas.

NASA (1995). Man-Systems Integration Standards, NASA-STD-3000 Volume 1, Revision B, Section 3.0 Anthropometry and Biomechanics. 3.2-3.3.

NASAexplores (2001). Make Room For One More Astronaut, published December 13, 2001 on www.nasaexplores.com/lessons/01-086/9-12_index.html accessed February December 13, 2001.

Rashid, K. (2001) accessed November 11, 2001 www.canadianinteriors.com/kmj01ns.html.

www.spacetoday.org/images/SpcStns/ISSafter8a2002.big.jpg accessed May 22, 2002.