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Exploring the challenges of habitation design for extended human presence beyond low-earth orbit: Are new requirements and processes needed?

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Abstract

With the renewed interest in a sustained human presence beyond low-earth orbit, habitation in space, on planets and on moons is an area that requires re-evaluation in terms of mission and habitat design—there is a need for a paradigmatic move from a design focus on short-term LEO missions to that of long-term missions in LEO and beyond. We claim that a design lock-in may have occurred over the last 50 years which will need concerted effort to be unlocked and realigned to suit the emerging long-term mission paradigm. In this paper we explore some of the issues and possible ways of infusing relevant insights into the space habitat design approach by seeking to bridge lacunae in both the design process and training of the next generation space design workforce. As early career researchers we explore these issues in a moderate way and with limited resources, through an exploratory design workshop, organized under the aegis of the Aurora Programme, with the aim of exploring multidisciplinary design and a view to understanding the potential benefits of interdisciplinary approaches and possible gaps in the current space design paradigm. We touch the tip of a very large iceberg, but close the paper with first round recommendations for further exploration within the space design community and to be supported by national agencies.

Keywords: Habitat; Habitation; Design; Interdisciplinary; Moon; Mars

1. The design challenge posed by human habitation beyond LEO

With the renewed interest[1] in a sustained human presence beyond low-earth orbit, habitation in space and on planets and moons is an area that requires re-evaluation in terms of mission and habitat design including the design approach itself. For roughly 50 years the space sector has been involved in trying to place and sustain human beings in space. In the early days of design, a particular systems-element suffered the most compromise during the design process—the passenger. This was due to a number of political and economic pressures to speed up access to space. In addition, these early stages comprised passengers originating from the military, where compromises on accommodation were already the norm and dealing with such restrictive and

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[1] Examples include the US Vision Programme, the ESA Aurora Programme, Chinese human spaceflight agenda, etc.

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uncomfortable spaces was inherent to the training of such pilots/passengers. Naturally those charged with space habitat design are aware of many relevant human factors and the requirements that can be derived from them; however, a consistent choice has been made to assign a lower priority to these requirements, in favour of other more cost-effective (and time-effective) priorities which has led to, for the most part, the generation of successful designs that were at the very least adequate for the duration of the mission.

For long-duration spaceflight and for planetary exploration the human becomes more central to the system, and other factors play a more important role in the efficiency and well-being of the passenger. There are a great many uncertainties related to interplanetary missions, and the economic and human costs relating to such uncertainties mean that mission success will depend greatly on elements previously exogenous to the systems design process.

Traditional engineering design philosophy based on LEO missions has led to designs that, while being equal to the task, have had other design drivers playing a dominant role, at the expense of certain human factors. This meant that the design team has always afforded themselves certain liberties with those passengers who would inhabit their design, as typical mission duration has traditionally been short-term rather than long-term.[2] In addition, the designer could rely on military training and professionalism to cover for the design compromises made at the inhabitants' expense, and accordingly, fill the lacunae in the design process. However, as missions become more long-term, the habitat must reflect such a choice by accommodating the fact that a passenger cannot be on duty for extended periods for long-duration missions. In addition, passenger profiles may change as the missions become more diverse, research and tourism being the obvious possibilities for Earth-orbital platforms. A major bottleneck (and a necessary one with current designs and missions) is the turn around for training. Imagining a future system of pilots and passengers where passengers have rudimentary knowledge of space systems would mean changing the design of the habitation modules and for researchers, a deeper look into the human–machine interface in the laboratories and other facilities where users would need to have minimum training to be able to use them.

For lunar and interplanetary missions, staffed by highly trained astronauts, one could infer that with increasing mission duration the habitat must assume the role of a traditional domicile capable of functioning simultaneously as workplace, home, hospital, gym, recreation area and so on, with social interactions having greater similarity to those on earth than previous short-term missions. This is of course contingent on the humans inhabiting the spacecraft or planetary habitation complex (scientists, military, citizens with minimal training).

Human factors, especially those with respect to habitat design (i.e. habitability) must always be seen within the context of the mission. Meaning they [1] 'must be considered and defined relative to the duration of the tour or occupancy and to the purpose of the occupancy'. What is considered tolerable for a short mission to the International Space Station may be completely inappropriate for a mission to Mars. What is clear, however, is that these habitability issues must be allowed to play a greater role in the habitat design process.

This translates into a *General Diagnosis* of the current situation:

- There *are* new challenges specific to the goal of prolonged human presence beyond LEO.
- These new challenges translate into *redistribution of weighting* of the design considerations and thus a need for non-traditional (with respect to space design) knowledge and experiences.
- Current elements exogenous to the systems design process may need to be endogenized for design AND mission success.
- Integration of these new knowledge bases may take the form of experts advising the present system engineers OR an integration of these knowledge bases into the design process itself.
- In the case of the latter, there is the issue of how best to accomplish this.
- The final diagnosis is that if a new process of human inhabited system design is necessary, how is the lock-in to the current space design process, which has been evolving for the last 30 years, to be broken and forged anew?

Presently the prevalent approach in the space industry is orchestrated through systems engineering which coordinates all the relevant disciplines in the most cost-effective and efficient manner based around trade-offs with comparative elements grown from over 50 years of design experience. This approach has also been augmented by adopting a concurrent character to allow for shorter lead-times, a better failure coping mechanism and innovative solutions in complex systems and products. This design approach is by far the

[2] Although the Soviet, and later the Russian, space station programme is an exception.

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dominant design paradigm in the space sector and has been steadily/incrementally improved upon.

When considering space habitation one need not argue for a multidisciplinary approach. This assumption need not be qualified due to the very nature of the complexities of artificial environments for human habitation. Beyond this assumption, as an entrance point to this paper we start with a number of claims.

Current disciplines are weighted based on historical bias inherited through lock-in to a short mission duration design paradigm. This means that those disciplines exogenous to the now stabilized method of systems design for space missions are evaluated with the criteria developed for those currently endogenous to the present design process. In addition, the *multi*- of multidisciplinary is ambiguous since this blanket term may cover many or few multiple disciplines; an investigation into relevant disciplines is called for. In addition the much-touted mantra of interdisciplinary strategies to design should be qualified. What does interdisciplinarity mean in this case? Multiple disciplines collected in concurrent engineering design approach similar to the concurrent design facility (CDF) in the European Space Agency's ESTEC? Or perhaps something more than the collective disciplines through the sharing of design approaches and more blending and mixing of perspectives?

The scope of this paper is to explore the claims we make about multidisciplinary design. We hope to build up an argument for reifying interdisciplinary space systems design for inhabited pressurized volumes and make a first *moderate* step at exploring these issues more deeply through a small pre-phase 0 design exercise bringing in multiple disciplines. We do this by creating a week-long design workshop, hosted by the European Space Agency's ESTEC facility, for educating people from various disciplines about current and possible future habitation system elements and their interplay.

After summarizing the design exercise, we will open up the discussion on space design for inhabited volumes in an attempt to kick start the relevant expert communities to take a renewed look at both extra design elements for habitation, criteria for assessing the effectiveness of these new elements and where in the design process can experts in these new elements become involved.

2. Exploring the challenges via the habitation design workshop

A first step in addressing this diagnosis was taken by organizing a concurrent design exercise, where participants were selected from a broad range of disciplines.[3] This project was initiated itself by a multidisciplinary group of organisers, who came together for the first time in addressing the lacunae mentioned in the diagnosis above.

The organizing team identified a number of possible problems with current habitat designs, the design process in place and with the next generation designers[4] themselves:

First, those designers originating from space science and engineering disciplines are not satisfactorily prepared, lacked rudimentary expertise in human factor derived requirements.

Second, those in architecture, industrial design, but also biology and medicine whose focus is on, or related to, space habitation and human aspects of spacecraft engineering[5] are not adequately prepared with respect to 'engineering' requirements and evaluation criteria. This is a barrier to interfacing expertise.

A *third* problem, which features in the aforementioned but deserves particular consideration is that interdisciplinary interaction besides focusing on different requirements and formulating requirements differently also suffers problems of jargon, different criteria for evaluating the optimum design and different design processes.

Fourth, the capacity to build up a multi- (or inter-) disciplinary space design workforce is hampered due to the path to the space sector being much easier to navigate for those in the 'usual' space science/engineering disciplines than for those from other non-typical but habitation-relevant disciplines. This is a major issue, since if we assume that expertise in the humancomponent is underrepresented in the design process, we need

[3] This project was created in a tight time frame of 12 weeks with the announcement of the workshop 4 weeks prior to the event. We received 150 applications for the 30 places. The workshop was hosted by the European Space Agency Aurora office, and organization and preparation was executed by 10 post-graduate and PhD researchers outside of normal working hours.

[4] These four possible problems were identified based on the experiences of the post-graduates and PhDs involved in designing the exercise, who themselves originated from different disciplines (space science, aeronautical engineering, space systems design, architecture, industrial engineering). The original intention of the exercise was to provide a platform for educating post-graduates about human space system design; however in the development of the workshop these problems arose, and were deemed worthy of particular attention based on the wider ramifications for future long-duration orbital and planetary missions.

[5] This could relate to man–machine interfacing which can be for both habitation and human work tasks in such a spacecraft or planetary complex.

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a trained workforce that can work together in a constructive and efficient manner.

The first three problems can be attributed to what is perceived as a knowledge/education gap. As far as the authors are aware, while many university departments (of the aforementioned space habitat design relevant disciplines) organize projects that allow students to develop familiarity with concepts like systems engineering, concurrent design, etc., there seems to be less focus on the interaction in a multidisciplinary setting and even less interest in providing exercises similar in nature after students and young professionals have become specialists in their field, at the interface between university and industry. One could argue that this is exactly the location where initiatives would be most needed, as it is here where the student or young professional would need to learn how to integrate him/herself and his/her specialization into the broader picture of habitat design. Note that at this interface students are of such a level as to be able to make meaningful contributions as well as learn in interactive exercises.

To this end, the Habitat Design Workshop was proposed to the European Space Agency Aurora Programme,[6] in order to explore the challenges derived from the general diagnosis of the previous section and these educational problems. The interest from Aurora was enabling excellence and building capacity in the space design workforce to contribute to its goals (robotic and human exploration of the solar system) and to ESA's goal of stimulating education in areas where ESA could play a key role as facilitator.

Furthermore, it was foreseen that the workshop could provide a platform for the participants, from both traditional and non-traditional disciplines, to create inroads into the space sector.

2.1. The workshop design concept and implementation

For a complete description of the Habitat Design Workshop we refer to Robinson et al. [3]. Here we will give a short overview of the workshop and highlight some areas pertinent to our discussion.

The workshop allowed for several design teams, each addressing a different mission scenario, similar to actual mission scenarios as suggested by US and European space agencies. These design teams were composed of students and young professionals from different space habitat design relevant disciplines: engineering, space science, architecture, industrial design, ergonomics, medicine and psychology. Each team comprised an engineer, an architect, a designer, a scientist and a human factors representative (Fig. 1).

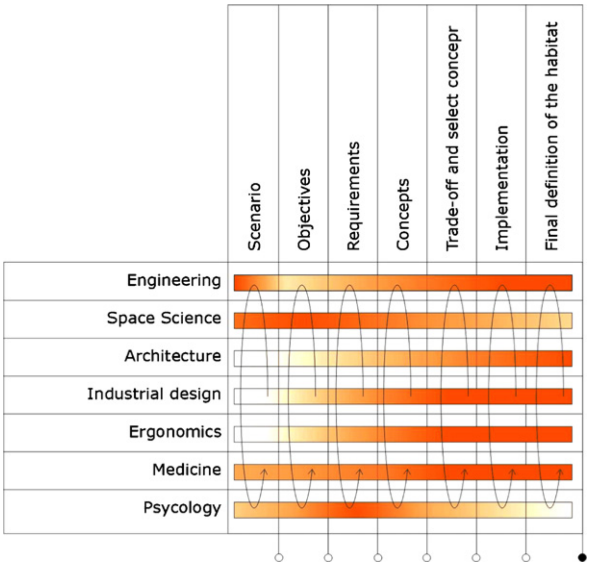

Fig. 1. The multidisciplinary dynamic and design process emphasis.

Five broad scenarios were drafted by the organization, similar to those found in literature and mission concepts from ESA and NASA. Two Moon scenarios, two for Mars and one for Phobos. To allow for a more creative process design teams were allowed to modify their mission scenario, but in keeping with the idea of building capacity and preparation of workforce for Aurora, a restriction of short-term (1st outpost) design objectives was imposed. The choice of which phase of the evolution of extended human presence beyond LEO the team should design for very much affects the balance between constraints and freedoms as they differ vastly depending on which point in the future one is designing for. This immediately proved to be a challenging phase of the design process as these first attempts at communication between different people, from different disciplines, with different social backgrounds, different cultures and different psychological characteristics required establishing a common ground.

2.1.1. Expert lectures and feedback

A number of experts lectured on relevant topics such as ISRU, the 'engineering' approach in practice, space science and the design considerations derived from human factors. The experts' role was twofold: to enable an overview of the relevant issues to bring the disciplinary representatives (the participants) in synch with the larger collective of systems elements (architects learning about

[6] For more information on Aurora see www.esa.int/aurora or Messina [2].

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radiation, engineers about psychological issues, etc.), familiarizing each participant with concepts outside the normal scope of their field, and to provide feedback where necessary during the exercise.

2.1.2. *Definition of the mission objectives*

Following from the mission scenarios each team defined the objectives of the mission and subsequently translated these objectives into requirements of, and constraints on, the major subsystems such as power, life support, radiation protection, telecommunication, dust removal, etc. required to achieve the mission. A large list of design drivers was discussed during the workshop which is presented in Box 1 below.

List of key design drivers was discussed during the workshop

Impact from micro and macro objects
Radiation
Temperature
Pressure
Exo Biology
Dust
Gravity
The external/internal interface
Deployment and packing configuration
The minimum crew needed in terms of habitability
Different possibility of in-situ assembly
Future base expansion
Mobility on site
Habitat construction options
Adaptability to changing mission requirements
Reaction to changing user-preferences
Human/machine interface
Safety
Layout design so as to facilitate ease of human motility.
Thoughts about the social and organizational aspects of life in the base
Social and psychological issues (effects of stress, recreation and exercise, interpersonal dynamics in space, personal space, privacy, crowding, territoriality

2.1.3. *Daily comparison session*

A daily session of group reviews was scheduled allowing for a step-by-step inspection of the developing designs. Comparing designs not only motivated the teams and therefore the design process but also served to minimize delays.

2.1.4. *Prototypes*

Each team was encouraged to work as visually as possible, especially in the beginning. Use of images and models seriously enhances communication and allows mutual learning about jargon and how each discipline frames a problem in their own perspective. Prototypes were often constructed in the form of small models, drawing, and 1:1 experiments up to full 3D renderings of habitat concept. These forms of visualization were discovered during the design process to be much more powerful than hoped, especially in the hands of those well-versed in graphics software and from the very first day visualizations were made, advancing the design process much faster than anticipated and made for a smooth design process and greatly facilitated communication within the teams.

For a full review of the workshop designs we refer to Robinson et al. [3] and Aguzzi et al. [4]. Here we will only mention two of the five designs as they serve as good examples of synergy between the space habitat design relevant disciplines.

2.2. *Example 1: A first stepping stone for a continuous human presence on the Moon*

The mission was to take place in 10 years, resulting in a permanent outpost in just three launches using the Energia launch system. The base would consist of the lunar lander modules with inflatable ovoid domes but future concepts would link up several ovoid structures together as the base expands (Fig. 2).

The concept design was the first of a series of missions to place a permanent base for humans on the Moon within 10 years. Minimal mission duration was 3 months. The project refers to technologies with a high TRL: Melissa derived system for life support, inflatable material and radial deployment system (Transhab derived), aluminium for core material (like ISS) and Nuclear power production (already flown in Russian satellites). The habitat design is planned to be flexible not only as a single unit, but also for future expansion when additional modules are added to a web-like ‘Moon town’ where different modules can be specialized into certain functions like a module allocated solely for living or science (Fig. 3).

The two-floor design is partially open without separation in order to give the crew the most spacious living conditions possible. The proposed layout offers a lot of freedom for reconfiguration using inflatable

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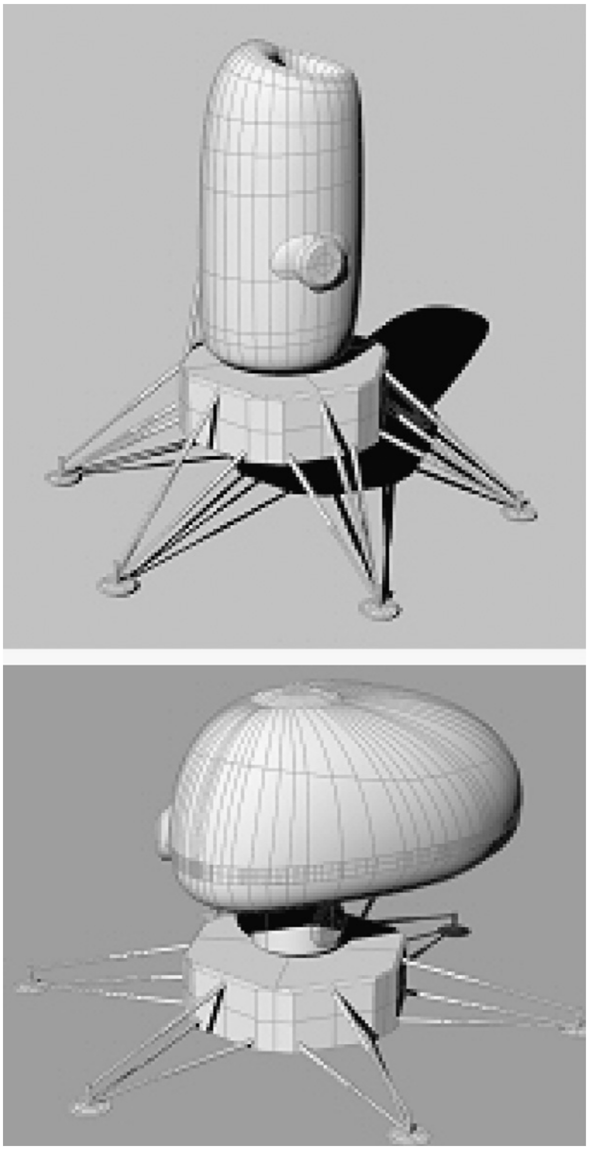

Fig. 2. Deployable habitat using Inflatable Technologies.

technology. The definition of public and private areas and its mutual relation is the main strategy adopted to generate the internal layout (Fig. 4, Table 1).

The team provided a clear presentation of their concept with references to social design components, bridging the gap between the technical feasibility and human factors. Shielding the light habitat structure seems to be one of the technical flaws of the design. Proposing an expansion plan in the design concept was a positive effort, yet in the 2nd round design it would need to be better integrated to the structural and spatial concept. The team succeeded in implementing a concurrent design approach beyond the traditional engineering by

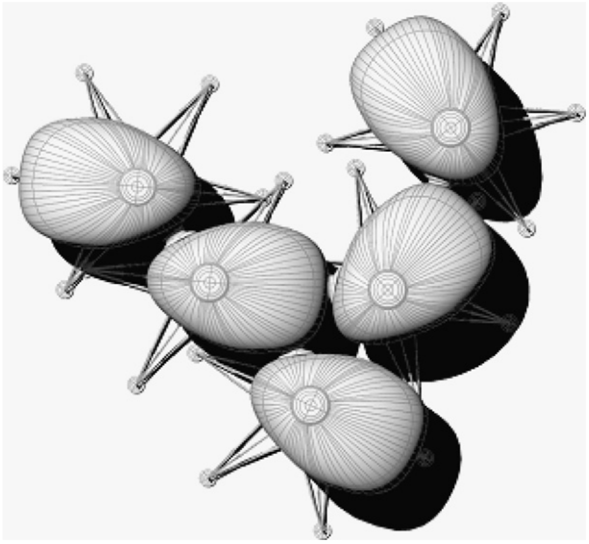

Fig. 3. Possible modular configuration of five modules.

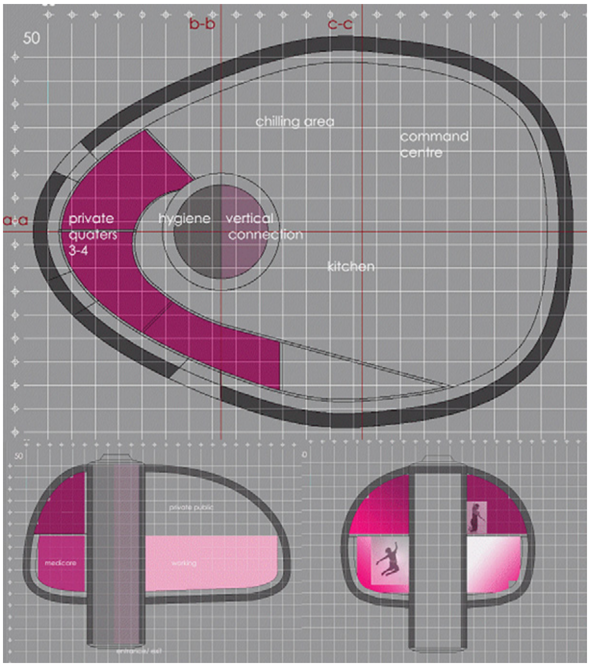

Fig. 4. Relation of the different functions to each other.

including psychological and social aspects. They included present day technologies as part of the design, which, although not all of them are space tested, are reasonable for a 1st generation lunar base.[7]

[7] This design was undertaken by: Arno Wielders (Netherlands, Physicist/Engineer), Jesper Jørgensen (Denmark, Psychologist), Julia Tizard (United Kingdom, Physicist), Ania Fischer (Germany, Architect), Stefano Zanini (Italy, Designer/Ergonomist), Hanna Västinsalo (Finland, Biologist).

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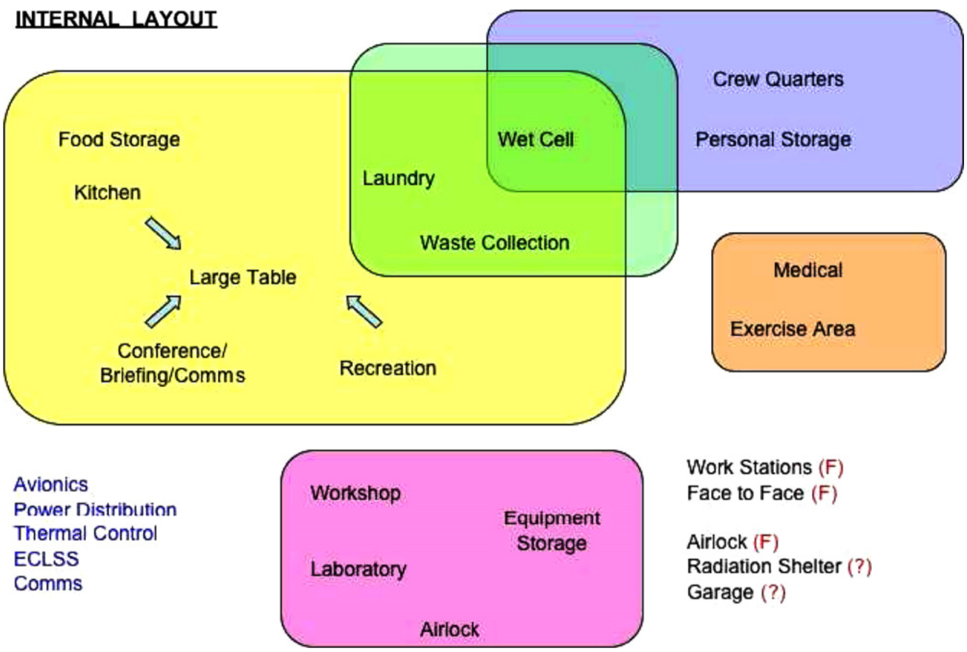

Fig. 5. Schematic of initial habitat subsystems based on qualitative and quantitative data.

Table 1
Elements of the Moon habitat

Item	Volume	Mass	Area
Inflatable: ceiling		1040	80
Floor		1040	80
Sides	91	3640	
First floor		975	75
Core: ceiling		100	5
Floor		100	5
First floor		100	5
Sides	8.5	500	
Total (kg)		7400	

Total volume of inflatable structure: based on 9 m diameter and a 11 m height cylinder: $\sim 800\,\mathrm{m}^3$

Consumables	Standard	Comfort (%)	Total
Food	170	200	340
Water potable	1000	150	1500
Water non potable	7000	100	7000
Oxygen	210	100	210
Total (kg)			~ 9000

Power included: 3 tons for nuclear system and 1 tons for fuel cells: total: 4 tons

2.3. *Example 2: To establish the core unit of an expandable outpost for Mars exploration*

The central modules performed a dual-role as a radiation shelter as seed for an expanding base, rather like a beehive of hexagonal stilted pods with inflatable domes. The initial crew of six on a 600-day mission would be there to do comprehensive science but the motivation would be exploration and adventure. The base was not linear so there would be plenty of escape routes should one path become blocked. A very in-depth study, which appeared to leave no stone unturned and yet keep the freshness and excitement of what is essentially a pioneering mission, was undertaken.

For the first manned mission to Mars, the team[8] proposed the establishment of an expandable core unit for the exploration of Mars at an equatorial landing site. Effectively this would be the ‘seed’ mission for the development of a constantly manned and maintained settlement. The core unit is designed to allow for easy expansion in a variety of ways. The duration of the first crew rotation will be one synodic year, and their outpost will be a stationary base (Fig. 5).

The design went through a series of phases; inflatables were utilized in the final design. During the entire development of the habitat design, safety was considered as the main systems driver. Both the internal design of the habitat and the honeycomb-like nature of

[8] This design was undertaken by: Gabriele Messina (Italy, Aerospace engineer), Nathalie Pattyn (Belgium, Medical Doctor/Psychologist), Emily MacDonald (United Kingdom, Astrophysicist) Nina Mair (Austria, Architect), Nils-Peter Fischer (Germany/Sweden, Architect), Julien-Alexandre Lamamy (France, Space Systems engineer).

the base after expansion allowed for the sealing off of any area hazardous area in the event of an emergency, leaving all remaining areas accessible. Internal configuration as well as flexibility of reshaping the internal configuration were certain aspects.

Based on conventional prefabricated modules, enriched with inflatable extensions, the Mars 2 Team proposes a concept using current technology with a reliable expansion system. The concept allows expansion of the habitat based on the core unit.

Though the structural approach is based on conventional Apollo-like design, the smart internal layout, use of inflated extensions for spatial flexibility and the well-defined expansion concept shapes this well-functioning Mars habitat. The shielding of the light structure is as usual a technical challenge to be solved. Various layouts, a little more investigation into the types of exploration and mechanisms of doing so would have improved the design, adding more functionality.

The team distinguished themselves from the very beginning by good communication between its members. They clearly defined the scenario, the requirements and the main subsystems. This team placed particular emphasis on the psychological requirements of the internal configuration of the space. The final habitat was well described by 3D modelling, which comprised a first study of the internal configuration. Their proposed way of expanding the main module was quite original (Figs. 6 and 7).

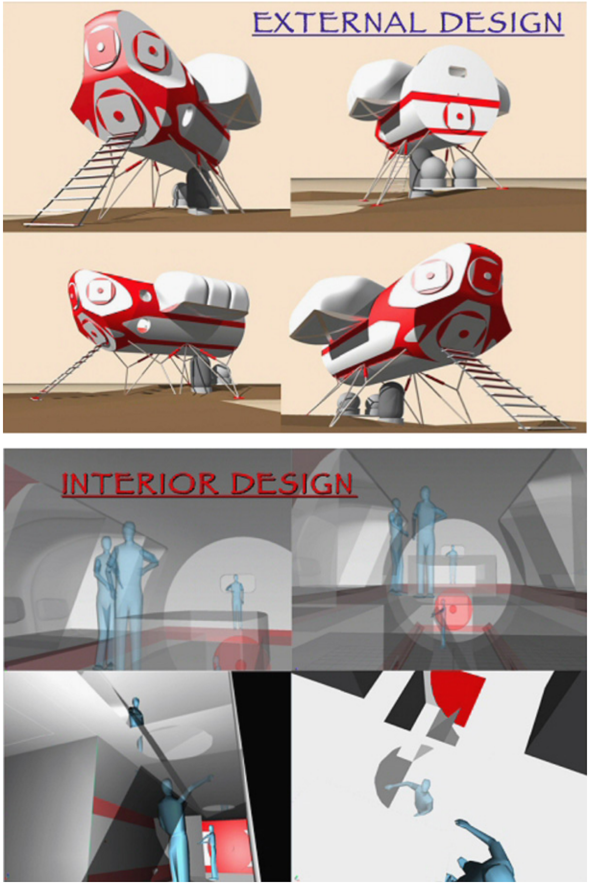

Fig. 6. External and interior design.

3. Reflections on the workshop and lacunae it exposed

3.1. There are new challenges specific to the goal of prolonged human presence beyond LEO

The workshop illustrated that inclusion of previously omitted habitability issues is of paramount importance to prolonged human presence in or beyond LEO. However, acceptance of these issues and the design requirements that can be derived from it also means accepting, to varying degrees, inclusion of these hitherto unconventional disciplines into the design process. This is accompanied by problems such as those highlighted in the above: these 'new' space habitat design relevant disciplines bring with them their own requirements, their own formulation of those requirements and their own design process of addressing these requirements. Moreover, they have their own jargon making it difficult at best to relate and translate their interests to the more conventional disciplines.

3.2. A redistribution of weighting of the design considerations is called for and hence non-traditional disciplines must play a greater role

It has been argued that inclusion of other human factors related disciplines in the design process, from the very start is pivotal for a well-balanced design that caters to the relevant requirements. Where previously human factor derived design considerations were considered of a secondary nature, i.e. such considerations were only made *after* the engineering design considerations had been implemented into the design, now there must be a shift of weights of design considerations. With increased mission duration, human factors are not just afterthoughts; they have become mission critical design considerations. There have been precedents of inclusion of such exogenous elements into the design process. The ESA AURORA human mission to Mars (HMM) study [5,6] included architects into the design process. Also in a recent study by Alenia, industrial designers were

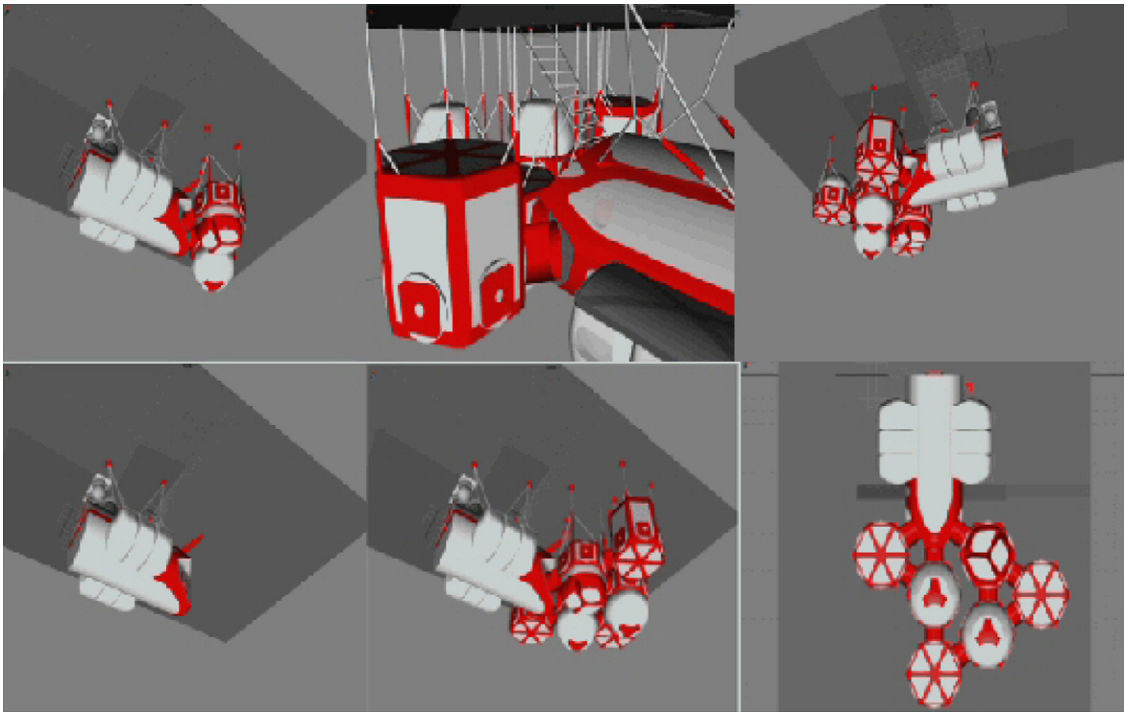

Fig. 7. Expansion concept.

included to explore other human factor requirements for the design [7]. This demonstrates that it is possible to include new elements into the design process. Having said this, architecture and industrial design approaches still remain exogenous to the core design process and criteria for uptake of such input will still remain based on the endogenous criteria. This is important because evaluation mechanisms [8] will differ widely for these new elements (which could be argued are necessary for long-term human spaceflight and planetary outposts). Therefore there is a need to explore whether these elements integrated in such ad hoc projects mentioned above should be included into the core design process and if yes then how they can be included as an endogenous element of the system design process.

These considerations were brought to light by most of the design teams. As each represented discipline brought its design considerations to the table, along with suggested ways of interpretation and implementation, the design takes shape. Such interpretation and implementation relate to the design approach by the discipline represented. These representatives frame the design issues based on their own norms, values and processes, and in this workshop we saw the first steps towards mutual learning *and* use of other disciplinary approaches. If such learning and use of different design approaches and framing of issues is continued, true interdisciplinarity may be possible, rather than multidisciplinarity (which brings disciplines together but does not necessarily involve sharing and application of each other's perspective).

However, what soon became clear in the workshop was that during but especially after the initial brainstorm sessions, when the design concept had started taking shape, the engineering disciplines were given and shouldered a leading role. In other words, interdisciplinarity is possibly a key factor in the design process but perhaps not required at *all* stages.

3.3. Design process and knowledge mismatch

It was clear at the outset that there were conflicts in the way to proceed with the design of the habitat. Some disciplines dominated the initial stages due to the institutionalized nature of systems engineering. For example, it was a general and recognized fact that the first decisions were mainly based on science and engineering, leaving the designer, architects and medical experts unsure of their role in the initial stages. Once mass constraints and the purpose of the habitat were decided; however, the engineers satisfied themselves with merely constraining the design to fairing size and mass possibilities (although in some cases, the engineers were forced to put aside their standard linear approach based on fairing size).

Psychological issues were strongly involved during requirement definition while design played the major role during the following phase where all requirements were synthesized in a visualized concept of the habitat. The speed and details of drawings and 3D models that the architects and (industrial) designers were capable of amazed both other participants and organizers alike. Working together taught the participants a great deal of respect for the other disciplines that will be useful for the rest of their careers.

The mismatch in design process and knowledge was evident, even amongst the invited experts. Conflicts arose in terminology and representation of the issues. Of note was the qualifying criteria framed in a quantitative (engineers) and qualitative manner (industrial designers and architects). Credibility of the assumptions made based on these two approaches were received with scepticism by those users of the other type of approach. Over time we saw these problems resolved (in some cases a truce was announced).

One team successfully blended the quantitative and qualitative approaches into a number of schematics which allowed the combination of details and the development of criteria for success. Another team was locked into conflict for 3 days due to the dominance of systems engineering approach and the lack of an entrance point for the industrial designers, psychologists and medics.

3.4. Integration of these new disciplines may take the form of experts advising the present system engineers OR an integration of these disciplines into the design process itself

An answer to this particular question did not present itself as such during the workshop because it did not become clear which was the better way: adopting the 'new' space habitat design relevant discipline *only* in terms of the derived requirements that are inherent to these disciplines but within the current design paradigm, i.e. the engineering approach, or incorporating more than just the requirements by trying to take advantage of the different design processes employed by the 'new' disciplines. Where engineers tend to progress along a rather linear stepwise approach, architects and designers, like to '*skip ahead*' in the design process and visualize what the design could be like in its final concept. This is a more visual, conceptualizing design process that can bring about new and unorthodox ideas. This iterative design approach is considered by both participants and the organizing team to be quite useful for quick evaluation of ideas without suffering much delay or setbacks.

Another related problem that may present itself if the 'new' disciplines are to be incorporated, in whatever fashion, into the space habitat design process, is that currently, to the authors' knowledge, access to this particular field for those who are active in architecture, industrial design and ergonomics and particularly biomedical disciplines is relatively limited. Workshops such as the one presented here can most assuredly help in creating links between industry and students, young professionals and establish sustainable channels for this up and coming space habitat design workforce.

3.5. How, if necessary, is the lock-in to the current space design process, which has emerged and stabilized over the last 30 years, broken?

The space habitat designs this workshop yielded, while innovative and encompassing in novel ways, did not exhibit explicit proof of superiority over what typical 'engineering' design teams could have achieved. It became evident that this is very difficult to evaluate. Designs have to be evaluated within the parameters dictated by the design considerations. Different evaluation criteria of what is a good design are different and linked with the different design communities and disciplines. Thus if a true comparison of design is to be made, evaluating human factors in the dominant systems engineering approach of the space sector may lead to *incorrect* evaluations of the human factors component.

Hence, more workshops (or other forms of probing each other's design worlds) need to be organized focusing on design, focusing on the advantages of an interdisciplinary team, and where in the design process they are most apparent. Workshops that focus on yielding results leave no doubt that these 'new' design approaches *need* to be considered for successful space habitats to become a reality.

With the ongoing development of commercial space ventures, i.e. suborbital tourism, transport, etc., medical protocols are being developed today, yielding human inhabited space systems design considerations that are more geared towards human factors. Thus there is a clear and present need for such considerations.

4. Issues for future space habitation design

One result that comes from this exercise is that one *can*bridge the education gap by doing these exercises like the Habitat Design Workshop but the *system* *elements and design lacunae*are more complex than one first assumes. One observation is that you can integrate different elements by bringing different disciplines together (and make some progress) but we found that *different design processes*(carried by the different disciplines) had fundamental differences, which dictated the shape of the design and the balance of inclusion of the various elements of the habitat design, i.e. prioritizing various design drivers and subsequent requirements. The major observation was that disciplinary design *process*is entwined with the effective inclusion of disciplinary *knowledge*. For true indisciplinarity, multidisciplinary design teams must be able to appreciate and use multiple design perspectives. If an aerospace engineer can grasp an industrial designers approach to framing a problem, there would be better exchange of ideas, and the opportunity to apply the strengths of both in solving the problem.

This workshop showed a glimmer of hope, augmented through the use of images and models, which allowed communication and mutual learning about approaches. But for lasting interdisciplinarity, the space sector will have to make a concerted effort to bridge the education gap and invest in such locations for probing each other's design worlds. Exposure to alternative ways of evaluation and design processes will augment interactions of various designers in future space projects, leading to more efficient designs. Thus a concerted effort to include these sorts of skills should be made. There is a role for space agencies here, by providing workshop-based activities (such as those supported through the Aurora Programme).

We have demonstrated that such workshops can be successful, and can improve through undergoing many such iterations. A number of experts participating in the workshop underlined; however, that although the Habitat Design Workshop was successful, for full success continued support/activities for those who attended would allow deeper learning and facilitate improved multidisciplinary design.

In addition we advocate that specific design challenges relevant for extended human presence beyond LEO be the focal point of such exercises, which will add a layer of focus and intensity to such workshops.

One must also consider which of these currently exogenous elements could be useful or could sap already limited resources. An initial diagnosis from our investigations shows that stimulation of interdisciplinarity at *early*stages of design process is attractive. But for later stages, we have little or no data on which to make a diagnosis. Therefore this is a challenge the space community must address.

In any case, a conclusion can be made that inclusion of such new elements in the design process would require the further development of evaluation protocols. Current cost-based evaluations may not be suitable here, as the human becomes more central to the system and quantitative analysis of success may be misleading. Thus there is a need to explore which are relevant and which are not and how they should be integrated into the systems design process.

The above leads us to a number of recommendations for the space (habitat) designcommunity[9]:

- There should be more of the training workshops for preparing the next generation workforce to enable present day explorations of possibilities based on those with some degree of experience in their own discipline.
- Evaluation of the disciplinary design processes is needed, with the aim of improving the integration of knowledge of the newly higher weighted system elements necessary for human missions to the Moon or Mars as the human becomes more central to the design concepts.
- There should be an evaluation of the broader subsystem elements and when/how they should be addressed in the design itself.[10]
- There should be an assessment of multidisciplinary (various system elements included in present approach to design—CE in systems engineering) versus interdisciplinary (where different design approaches are integrated to develop a final habitat design in an equal way). This should aim to answer questions such as: Is a change in design process needed? Would it benefit design?

We face considerable technical challenges if we are to sustain a human presence beyond LEO for a considerable amount of time. However, what we wished to do in this paper was to highlight that *the design process* itself will face considerable challenges and that it is high time that the process be revaluated with respect to the previously exogenous design elements which may

[9] These recommendations are targeted particularly at national space agencies which are in a position to support research into these broad and fundamental issues.

[10] For example, it is clear that for pre-phase 0 design exercises, as many aspects as possible should be included. However, as we progress through the design and development process to deployment of the system, where should previously exogenous expertise be integrated into the process? Is an evaluation protocol sufficient for assessment during later stages of the mission, or should relevant experts be included in some shape and form at later stages?

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become system drivers as the human becomes more central to the system and criteria for a successful mission change radically.

In our moderate way, we hope to have contributed a little towards this goal. Our 30 participants drawn from different disciplines experienced these challenges in design processes and integration of various system drivers first hand, supported by experts from the European Space Agency and elsewhere. However, we make no claim that we have solved any of the problems. Rather we have further articulated the problem and hope that we can move on from there, in order to create robust human inhabited space and planetary systems suitable for long-duration missions.

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