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Pillow talk—Curating delight for astronauts

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ABSTRACT

In a not so distant future, human explorers will venture farther away from the Earth. To enable long duration space missions, we need to advance space habitat designs beyond today's technological solutions, focusing on the astronauts' basic physiological and psychological needs. In addition, we must design for the crew's wellbeing and comfort, while reducing stress and enhancing their privacy. This goal can be addressed by designers and artists, who are skilled to lead facilitated conversations, create mock ups, prototypes, and boundary objects, with curated affordances that respond to astronaut needs. One of the simplest examples of an artefact that provides comfort to a user is a pillow. At first glance, the meaning of a pillow in zero gravity is not obvious. Yet, exploring it deeper, the space environment also opens possibilities for experimentations and conversations around a reimagined space pillow artifact, with broadened affordances, while also supporting vitruvian delight. For example, sti-mulating the limbic brain through the sensory system (including touch, olfaction, hearing, vision, and taste) reduces stress. In this paper we discuss our design process, which includes our rationale to select this unlikely artifact as a representative boundary object. We discuss the ideation process on form and function, from head support to attachments to the habitat's wall. We explore the materiality and aesthetics of the outer skin layer, and curated interactivity options through soundscape, light, and smell. Our first-generation artifact acts as a proof of concept with a subset of all possible affordances. It is a forward looking search, in line with second-order cybernetics, where the outcomes inform us towards the development of subsequent space pillow versions. We use this boundary object to initiate a conversation about facilitated interactions between objects inside space habitats and the crew, and exemplify how artistic and designerly processes can contribute to space exploration. We also discuss the need to address higher-level astronaut needs on long duration spaceflight, through an artefact that provides an emotional connection and bridge between the space travelers and their terrestrial home. During this process we also expect to broaden our concepts to other artifacts inside space habitats with user interactions and curated autonomy in support of discovery, learning, relaxation, comfort and wellbeing. By choosing a pillow as a focal point of this project, we are hoping to engage artists, designers, and space architects to reframe the discourse around space exploration, and to broaden today's technology-driven human space exploration para-digm.

1. Introduction

As we explore our Solar System, we will gradually leave low-Earth orbit, and the Earth-Moon system and venture to farther distances. The next obvious destination for human explorers is Mars. A round-trip mission to our planetary neighbor will take about 1000 days, which warrants the reassessment of accommodating the astronauts and ca-tering to their needs beyond basic physiological needs and safety. This translates to advancements in space habitat designs, beyond today's technological solution-based approaches. On short-duration missions, for example on visits to the International Space Station (ISS), the crew quarters seem frugal, as shown in Fig. 1. The personal space is very small and only affords the basics for resting and privacy. While long duration missions will face similar resource restrictions, the circum-stances will limit communications with the Earth and prevent re-supplies due to vast distances. The crew will spend their time inside the habitat in virtual isolation. Consequently, we need to augment the de-sign of these personal and public spaces on transfer habitats by ac-counting for the wellbeing and comfort of the crew. We also need to minimize stress [1,2] and enhance the crew's privacy [3,4]. Autonomy will play an important role in these designs, which must reach beyond today's technological solutions [5]. Thus, we need to introduce new

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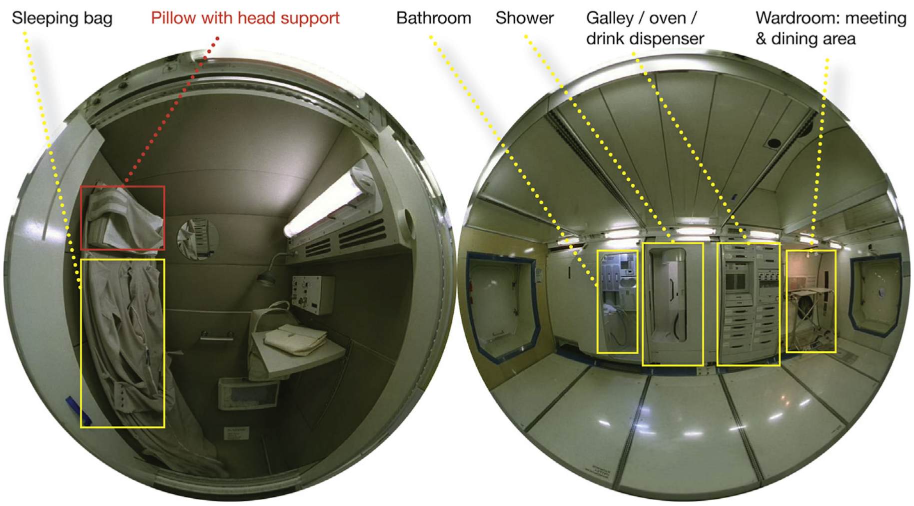

Fig. 1. ISS habitation module mockup, including the crew quarters (left) [NASA]. The design reflects a predominantly technology driven approach, including utilities distribution, supply lines, etc. From a human centered design perspective, it caters to the basic needs of the crew on short-duration missions. Sleep, eat, clean, toilet, socialize, all crammed into a limited volume-space. This design philosophy is also driven by resource limitations and sustainability.

disciplines to the design process, championed by designers and artists with the appropriate skill set to create curated affordances [6] that respond to the needs of the crew. These can be done through designerly and artistic processes, such as conducting user research to identify astronaut needs, building mockups and prototypes, and evolve design conversations through a forward looking search of the solution space and through creating boundary objects [4,7,8] that facilitate interactions, as discussed in Ref. [5] by Balint and Pangaro.

In this paper—as a follow on to Ref. [5]—we explore the topic of interactions between a crew member and his/her personal space on a space mission, with a focus on wellbeing. Such approaches play increasingly important roles on long duration spaceflight. The autonomy of this type of user–object interaction needs to be curated in order to enhance the experiences of the crew members and accommodate their higher level needs, according to Maslow's Hierarchy of Needs (HoN) [9,10], while also complying with strict safety requirements. Maslow's HoN—as applied to human spaceflight—is shown in Fig. 2, and further detailed in Ref. [4] in this context.

2. Design methods

2.1. Design methods through the design stages

In the initial phase of this project, we used a combination of design approaches for envisioning our artifact, while employing the "double diamond" design method [20], shown in Fig. 3. In the first diamond, or first design cycle, the divergence phase represents an exploration of potential personal artifacts that can support the wellbeing of an astronaut. After identifying a number of choices, in the convergence phase we identified the artifact that we wanted to explore further. In the second diamond, or second design cycle, we explored numerous options and variants for this artifact, then down-selected to the final design. We have documented the design iterations and forward looking search to a preferred outcome, which included initial conversations, background research, and employing de Bono's "Six Thinking Hats" methods [11]. The six colored hats are:

- White Hat (Facts and Information)
- Yellow Hat (Optimism)
- Black Hat (Judgement, Devil's Advocate)
- Red Hat (Feelings and Intuitions)
- Green Hat (Creativity and Possibilities)
- Blue Hat (Management and Processes)

We mapped the trade space using taxonomies towards an ontological [12] approach, then utilized hand sketches for circular sense-giving and sense-making cycles. We have used these sketches as boundary objects [4,7,8] to facilitate conversations between us, and subsequently with our audience.

These steps led us to a final design for the current stage of the

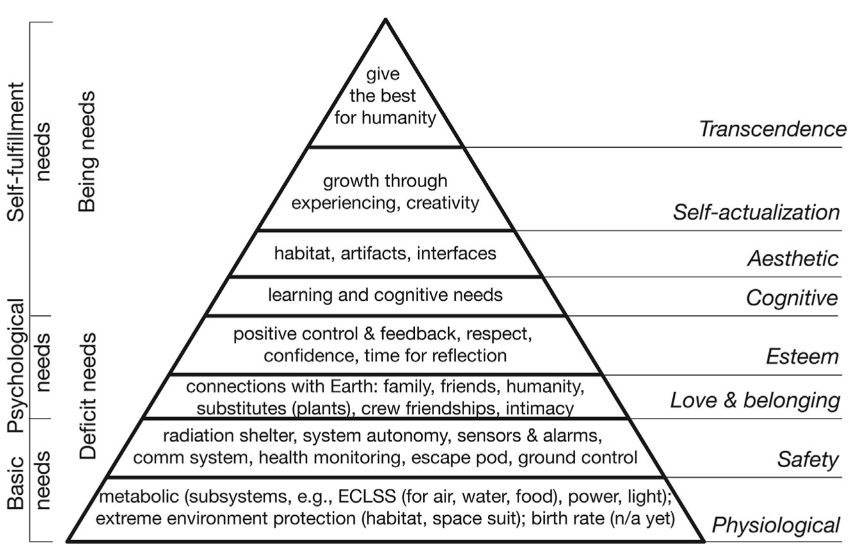

Fig. 2. Illustration of Maslow's Hierarchy of Needs (HoN), described in Ref. [10] (p.2&104), and applied to human space missions. The International Space Station (ISS), the Russian MIR Station, and the US Skylab exemplify current and past Earth-orbiting space habitat designs. All of them were designed through a technological paradigm, while addressing deficiency needs of the crew, which included basic physiological and psychological needs, and safety. Resupply and evacuation were part of the design considerations. These will not be available on a future human mission to Mars. In isolation, addressing higher-level needs becomes an important design driver.

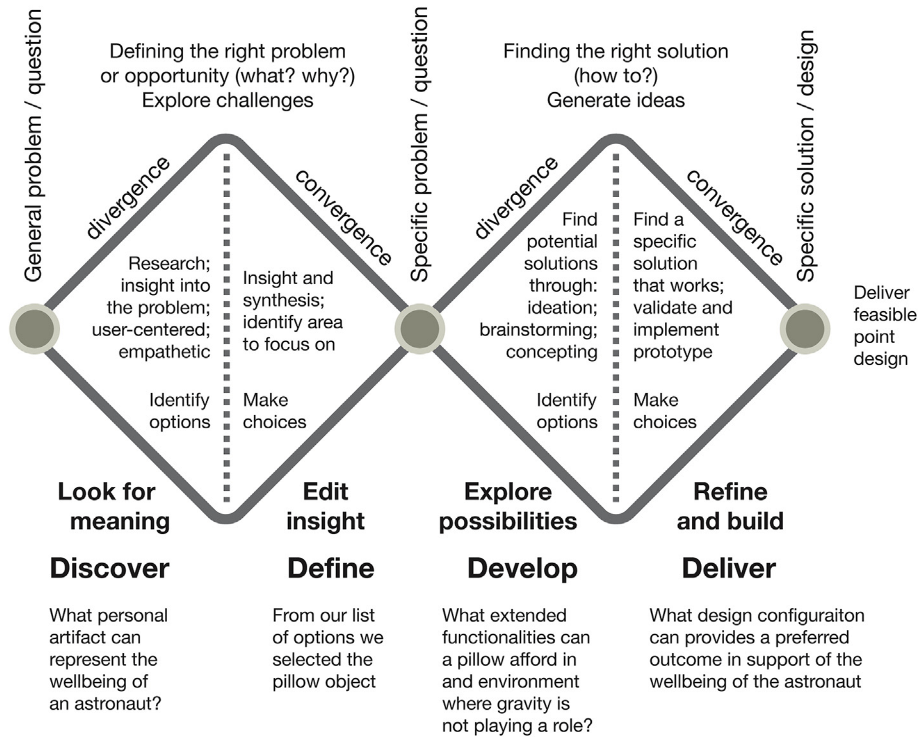

Fig. 3. Illustration of the "double diamond" of design model after the Design Council [20]. It shows two linearly connected divergence and convergence phases, as applied to the current design process.

research activity, which we illustrated using a 3D graphics software (Blender3d).

We also differentiated between two circular design interactions. The first relates to designing the artifact, which consists of sense-giving and sense-making cycles between the designers and the artifact. The second is a similar but subsequent cycle, between the user and the artifact, as discussed in Refs. [4,5,13].

In addition, we leveraged our past experiences to address this design challenge, including our doctoral research topics at the Royal College of Art, ranging from human centered design for space habitats and cybernetics [4] to design interactions for synesthesia [14].

2.2. Design ontology and taxonomy

An important outcome of this project was the introduction of an ontology/taxonomy approach to the design trades. Ontologies and taxonomies represent similar concepts. While a taxonomy describes a hierarchical construct, such as parent and child, an ontology provides more complex and seemingly unconnected relationships between various aspects. For example for an ontology, a person could be a graphic designer (belonging to a class of designers), also have brown hair (a class of brown haired people), who likes walking (a class of walkers), who lives in a village (a class of village folks).

Taxonomies are built around well-understood trees and can be a bit casual. Taxonomies can be represented in graphs that include nodes (or universals), as well as sub-classes (referred to as "is_a") relations [12]. A taxonomy can be a logical construct, it could use keywords about the covered subjects, but potentially multiple entries can be associated with the same keyword. While taxonomies don't include descriptive keywords for each aspect, ontologies include vocabulary-terms to specifically define each meaning in order to provide an appropriate distinction. For example, "is_a" can have multiple meanings. Among others—using Juno as a specific example—Juno "is_a" …. an "orbiter" that is a thing; or "a spinner" that is a behavior, as well as can be a roman mythological figure, the daughter of Saturn. So, this type of language is not sufficiently specific for an ontology.

Ontologies tend to be rather specific, leaving little to misinterpretations by the observers. Ontologies cover a broader scope of knowledge. While taxonomies are hierarchical "tree" constructs, ontologies tend to compare better with a "forest," which may contain numerous taxonomies, organizing the subject matter in a desired way. A good and successful example for an ontology is from the field of biology, specifically the Gene Ontology [12]. It is the principal source for genomic research. The Gene Ontology (GO) covers genetic biological entities in three areas:

(1) cellular components;
(2) molecular functions; and
(3) biological processes.

Ontologies benefit from modular designs, and they promote reusability of knowledge for other applications within a given well-defined domain. Modularization could cover an upper ontology, that describes general knowledge; domain ontology such as the aerospace domain; task ontology on how to operate things; and application ontology for specific applications and processes. An application ontology can inherit knowledge from higher level ontologies. For example, in a design ontology we can include domain-specific elements, tasks, and processes. This is further discussed in the following section.

3. Designing the pillow system

3.1. General considerations

During long duration spaceflight crew isolation and monotony can be mitigated through circular interactions between the crew members and artifacts inside their habitat. Such conversations with the environment require well-defined and understood inputs and outputs, and can be harmonized through Human Material Interaction (hHMI) [15], using materials, surfaces, color, light, sound and smell to positively support a crew member. When designing for circular interactions between the user and the artifact, we need to identify the types of inputs and outputs for both of them. For an astronaut, vital signals are routinely measured, including body temperature, heart and respiratory rates, blood pressure, harness for ECG, breathing, perspiration, cholesterol level, and sleep patterns—including auditory signals related to snoring and sleep apnea. These can be used as input information to the artifact, as well as speech and movement for additional interaction possibilities. Conversely, we perceive our environment through sensory organs. That is, eyes for vision, nose for smell, ears for hearing, tongue for taste, skin for touch, and vestibular sensors for balance and movement. Artifacts can utilize analogous set of sensors to collect inputs from the environment which includes user generated ones. The perceived information is then processed through the user's cognitive model as well as through the algorithm built into the interactive object.

In our design process we derived ideas from past research, including among others, from a layered approach for furniture design [16], materiality [15], boundary objects [4,7,8], cybernetics [17], and synesthesia [14].

3.2. Why? What? How?

Why? At the beginning of this project the first question we asked was:"Why do we want to conceive a designerly or artistic artifact for astronauts?" This part is simple. We believe that in the not so distant future humans will venture increasingly farther away from the Earth. On such long duration space missions it is not sufficient to address the crew's basic physiological and psychological needs through technological solutions. We need to go beyond it by also designing for the crew's wellbeing and comfort, which can also help to reduce their stress and enhance their privacy. Furthermore, we are aiming to initiate a conversation on this topic, by using our artifact as a boundary object that facilitates conversations between various disciplines, including design, art, and engineering.

What? Next we asked: "What interaction do we envision between the astronaut and the artifact?" Interactions can be unit-directional or circular, both can support the emotional wellbeing of the user to varying degrees. Sensory signals can also be combined, including visual signals, touch, texture, color, movement, smell, sound and temperature. In a circular interaction between the user and the artifact, signals from the user can be collected and responded to by the artifact. These signals are temporal. For example, response by the artifact to touch or to auditory signal can be immediate. The signal information can also be collected and processed further. For example by using heart rate or breathing rate over a period of time we can design responses to promote relaxation. The interactions may also vary if the artifact is considered a personal item or a shared item between multiple crew members.

How? In the first design diamond stage of our process, shown in Fig. 3, we brainstormed about identifying a representative artifact that can address these considerations. Our goal was to focus on personal objects inside a long duration space habitat, that can facilitate interactions between an astronaut and the environment.

Our ideas in the divergence (or options generation) phase ranged from interactive communication devices, to toys, and various personal objects. After discussing the interaction potentials of these various artifacts and conversations with NASA designers and engineers, in the subsequent convergence phase we made our choice by selecting the pillow as our representative object. This personal item offers affordances that caters to comfort and addresses the wellbeing of a user through delight, coziness, and a sense of home while away from home.

In the second design diamond stage of our process we used de Bono's "Six Thinking Hats" system to explore the design space from six different perspectives, then created taxonomies around domain areas to explore the hierarchies and connections between diverse aspects of designerly and artistic considerations. We also sketched pillow options and down-selected to a final design.

While a pillow represents one of the simplest examples for a personal comfort artifact, at first glance the utility of a pillow in zero gravity might not be obvious. But, as we explore it in more detail we can re-imagine its functionality from a simple head support, to a multi-functional pillow system in a space environment. With broadened affordances and interactivity (utilitas) we reach beyond the normal pillow functionality, that is also well built (firmitas), and supports vitruvian delight (venustas) through design for the wellbeing and emotional needs of an astronaut in Mashlow's HoN [9,10], showing in Fig. 2. (With this categorization we refer to the three virtues of architecture by the 1st century BC architect Marcus Vitruvius Pollo [18].)

3.3. de Bono's "Six Thinking Hats" system

Once we identified the pillow as the main artifact for our project, we used Edward de Bono's "Six Thinking Hats" system [11] to ideate about the design options through parallel thinking, specifically through looking at the problem space from six relevant perspectives. As an example, we captured some of the relevant considerations below:

3.3.1. White Hat (Facts and Information)

Physiological and human factors play important roles on long duration spaceflight. Morphew states: "*We now, however, stand on the forefront of a new challenge. Our experience in long duration spaceflight has revealed that it is often the human element pertaining to poor human-technology interface design, team and interpersonal dynamics, spacecraft internal environmental conditions (habitability), and psychological factors that limit successful performance during spaceflight, rather than the purely technological factors of the environment.*" [2] Various stressors impact the physiological and psychological wellbeing of the crew, ranging from radiation, absence of natural time parameters, limited sunlight, altered circadian rhythms, sensory/perceptual deprivation, sleep disturbances. The crew members are isolated, can't be rescued during emergency situations, they live in a protective enclosure surrounded by the extreme environment of space. Psychosocial factors include crew interactions, multi-cultural issues, and social conflicts. Habitability is influenced by limited hygiene, chronic noise, limited sleep facilities and privacy, isolation, and environmental lighting. In this environment, a well-defined and configured personal space with support for rest, relaxation and sleep can greatly benefit the wellbeing of the crew members.

Our chosen object for this environment is the pillow. Typically pillows are soft. This can be captured by their materiality. In zero gravity there is no functional need for them, but they still provide an emotional support through coziness, touch, feel, and the smell of being home. They afford personal interactions with the environment. They often include three layers. The outer shall is represented by the pillow case, which can be customized by the user. It includes texture, color, and patterns. The medium layer is the actual shell that is longer-lasting and sturdy. The inner filling provides softness using various means ranging from organic feather to synthetic materials and foam with varying firmness. Pillows can be simply flat or shaped to the contours of the user's head. On space missions the volume is limited, thus sizing plays an important role. Between sleeping and resting or relaxing, the environmental lighting conditions may vary from full darkness to colors with varying intensity. When designing for a space habitat, the safety of the crew is paramount. For example, when choosing the right materials, we need to account for flammability, degassing, recyclability, and cleaning of any or all of the three layers.

3.3.2. Yellow Hat (Optimism)

As we progress forward with our human space exploration ambitions, we need to move beyond technological solutions to address the higher level needs of the astronauts. We offer our design as a small step towards initiating conversations around the topic. If we can design, build, and user-test a prototype pillow system, and demonstrate its added functionality, the outcome could be used to make a case for accepting and including this and other artifacts to support the higher level needs of the crew. We found that the pillow can be a

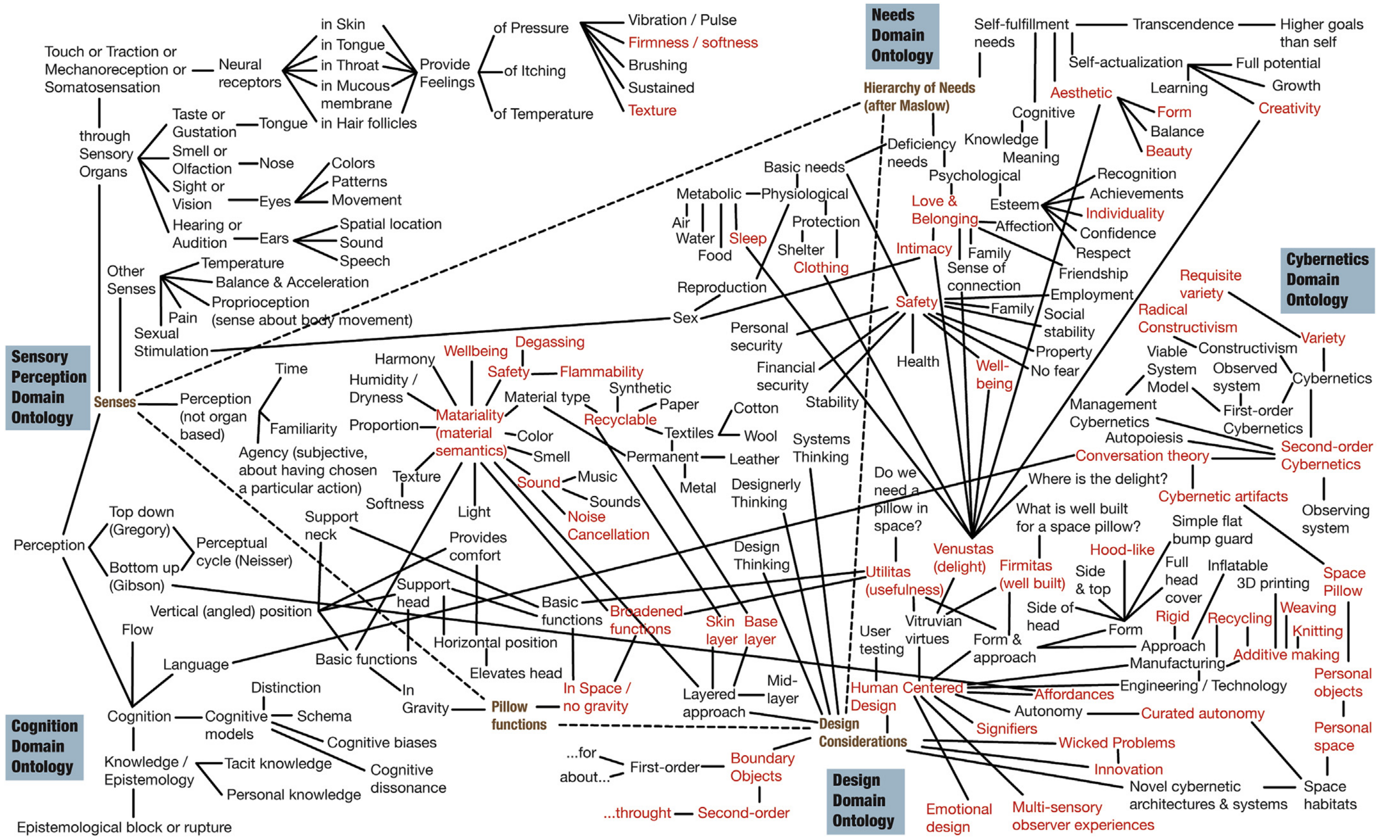

Fig. 4. Design taxonomy of the pillow boundary object, with initial implications towards a design ontology. The domains expand on key topic areas, including sensory perception, cognition, design, cybernetics, and Maslow's HoN. The red highlighted (and likely incomplete) entries indicate aspects where the taxonomies have relevance to the pillow concept. Interconnections between the entries need further work, as well as resolving the duplications of properties. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

representative artifact to make this argument. It is also one of the artifacts that we tacitly interact with while sleeping. Thus, a pillow system could be the first step to introduce a family of new artifacts to support higher level crew needs. By moving from a simple pillow to a pillow system with added functionalities, we might be able to redefine terrestrial pillow system solutions. A well-designed space pillow system may also become a novelty item on Earth. The design can align strongly with human space habitat materiality considerations, which were discussed in Ref. [15]. Finally, our pillow system design research is only a point of departure, and can present further development opportunities.

3.3.3. Black Hat (Judgement, Devil's advocate)

Pillows are not functionally required in zero gravity. Space missions are resource limited even without including frivolous items. If this design effort does not achieve its intended goal to promote conversations, it may hurt more our future efforts to design personal items, than not designing this pillow system at all. Without access to proper tools, including textiles, sewing machines, tailoring tools, we may need to approach outside help to develop the pillow. Time is also limited to complete a full design cycle with a resulting prototype. This will extend the project life cycle for a subsequent making phase. The topic might be "too designerly," and could be considered outside of the interests of a space-specific technical community.

3.3.4. Red hat (Feelings and Intuitions)

In support of astronaut comfort, we augmented the functionalities of the pillow system. While we increased the interaction capabilities of the design, we also concluded that it became too complex and likely uncomfortable for the user. Thus, at the end of the design cycle we decoupled the various pillow system functionalities. As a result, by moving away from a helmet-like design, we arrived to a preferred outcome by maintaining interactivity in a non-intrusive way.

3.3.5. Green Hat (Creativity and Possibilities)

Our iterative design process and brainstorming allowed us to explore the design trades for a broad set of artifacts, and within the pillow system explored its various extended functionalities. Considering the artifact to be a boundary object, we successfully ideated on various design options. For example, using the word "pillow" focused our brainstorming ideation around a space pillow, allowing us to explore creative solutions around the concept. Beside the typical touch and feel, we enhanced its functionality by using a broad set of sensory perceptions, including smell. For example, from conversations with friends and family we have found that two droplets of lavender oil can enhance sleeping. The temperature of a pillow or the temperature gradient across it can also benefit sleep. Consequently, redefining the meaning of a pillow to a pillow system in zero gravity can greatly enhance the opportunities to support the wellbeing of an astronaut. We can add sensors to it, speakers, other sensory feedback, modulate the temperature, change its shape, allowing to have a conversation with it, and play with other types of affordances. We may even find future solutions to create a gravity-like perception for sleeping, using a more advanced pillow system. We can also look at other possibilities for interactions, functionalities, and integration, including IoT (Internet of Things).

3.3.6. Blue Hat (Management and Processes)

Everything we fly in space must be qualified for crew and mission safety. The process is complex and involved. All materials must be tested and approved by complying with NASA Procedural Requirements (NPRs) [19]. Thus, it is important for artists and designers to have continued conversations with NASA engineers, who can guide material qualification activities through the design, testing, and integration processes. For this, designers need to create functional prototypes for testing, and mature the design through typical NASA technology maturation processes. These artifacts have to be tested in a relevant environment and approved before they can be included on a flight manifest.

3.4. Taxonomy and ontology mapping

We have mapped the human space habitat related object hierarchies into a proto-ontology, which at this stage is slightly more than a glorified taxonomy. In Fig. 4 we illustrate this by identifying specific domains:

1) the sensory perception domain is based on the human sensory system;
2) the cognition domain connects to the perception part of the previous domain, but also covers cognitive models, knowledge and language;
3) the needs domain is derived from Maslow's Hierarchy of Needs;
4) the cybernetics domain covers both first and second order cybernetics, which is important when considering interactions between the user and the environment; and
5) the design domain maps out concepts related to materiality, human centered design, form, function, and manufacturability.

In Fig. 5 we show the object domain specifically for the pillow, with a focus on configuration options, and how these relate to functions.

This exercise was highly beneficial to understand design considerations, design trades and options, and how they relate to each other.

While these are still in a taxonomical hierarchy, over time, and with refined definitions and interconnections they can evolve into a well-defined ontology.

3.5. Sketches

In the next stage we sketched out various ideas about the pillow system, illustrating a limited selection of broad and unbound speculations about potential configurations, as shown in Fig. 6. With these, we shared different feasibilities and concerns to discuss opportunities; introduced design; and explored what design can do for space-related innovations.

The simplest concepts cover versions of inflatable neck pillows. Some include a hood to block out light, and headphones for music and noise cancelation. Others move towards integrated soft- or rigid-helmet designs with a built in headphone, and a visor for light therapy. With each added element the complexity of the pillow system increases, enriching the interaction potential between the user and the artifact.

Another integrated pillow system is illustrated in our “*Space Angel*” design concept. It includes an inflatable ring that attaches to the head. Built-in components include speakers for music or other sound effects, WiFi connectivity to receive the signal, a dispenser for smell, and built in lights that can stimulate the user's eyes even in sleep. As the system senses that the user fell asleep, the pillow deflates and loosens from the head then passively detaches due to zero gravity. Here we are emphasizing the spatial and temporal relationships between the object, the user, and the environment.

It should be noted that these ideas are not necessarily unique. We encountered similar needs on Earth. There are numerous commercial designs available to enhance user wellbeing, as shown in Fig. 7. Inflatable neck pillows are popular among travelers, some include a hood to block out the light from the surrounding environment. Sleeping aids include soft eye pads, some with built in WiFi connectivity, speakers,

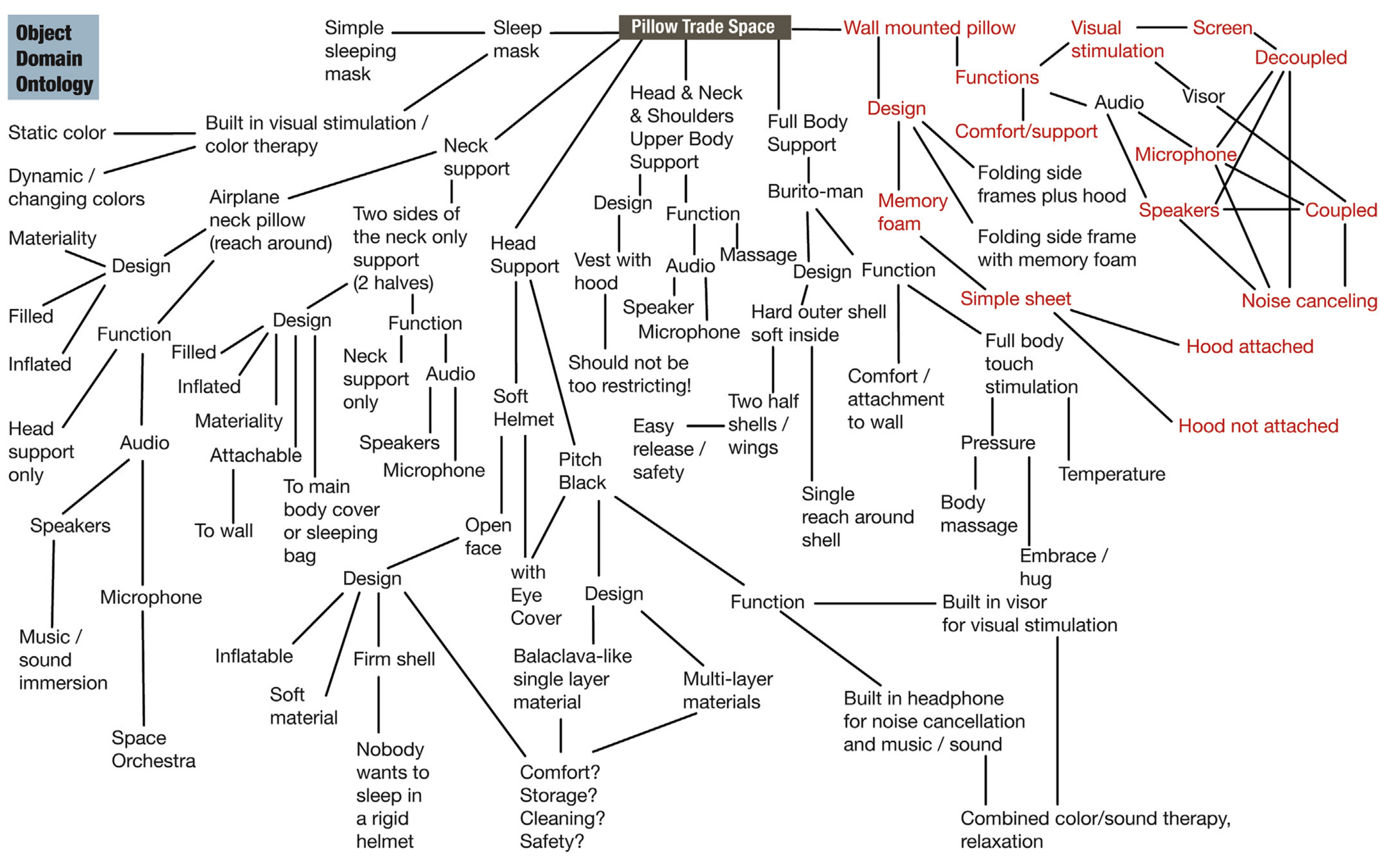

Fig. 5. A work-in–progress object domain mapping for the space pillow artifact. Since it is not yet a fully developed and resolved ontology, this taxonomy mapping has overlapping entries with the mapping shown in Fig. 4.

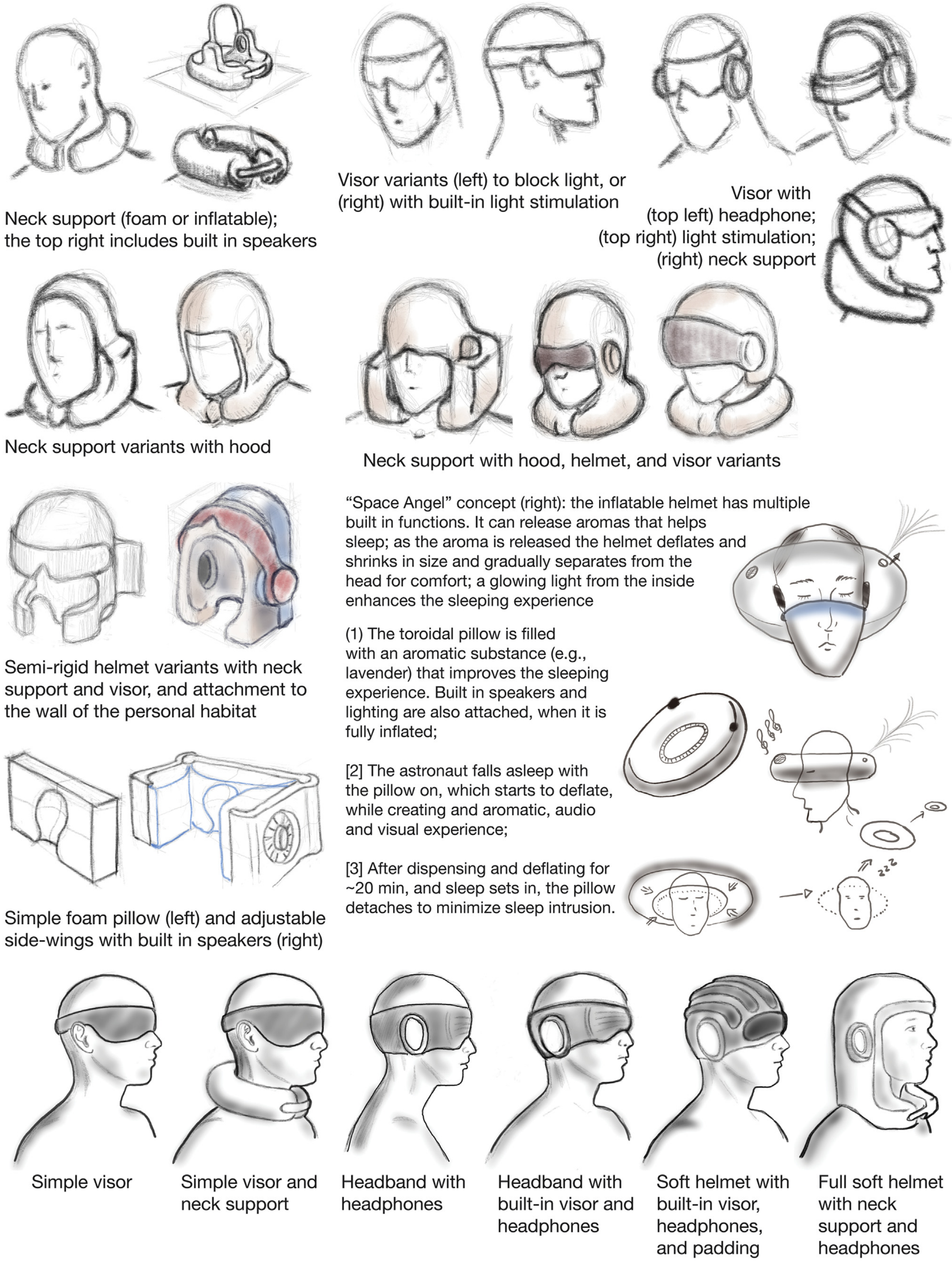

Fig. 6. Sketches to illustrate space pillow object trade options with various functionalities, as mapped out in Figs. 4 and 5.

Fig. 7. Commercially available solution examples, addressing the wellbeing of the user. Clockwise from the top left corner: Inflatable travel pillow and neck support; Neck support with a hood; Bluetooth sleeping eye mask with a built-in headphone and microphone; Airplane head rest; Color changing LED light panel; and CoeLux artificial sunlight. These approaches can be (and some are) used by astronauts inside a space habitat. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and microphones. Light therapy devices can mimic the light frequency of the sun or illuminate the environment in any given color.

These sketches and background research for existing solutions were beneficial to translate out ideas into boundary objects for conversations about the solution space and converge to a final point design.

3.6. Final point design

In the final stage of the current project we have evaluated the various options and made three conclusions. First, the pillow system with increased affordances can support the wellbeing of an astronaut during sleep or rest. Second, the helmet-like design where all the sensors and functionalities are built into the "pillow" is likely cumbersome and uncomfortable. It may even introduce safety issues during emergency situations. Third, the same functionalities can be supported in a decoupled way, where the various interactions are distributed inside the personal space of the crew member.

Such configuration builds on the approach used on the ISS by astronauts. A mockup of this configuration is shown in Fig. 1, while an actual "lived in" space is shown in Fig. 8. From the looks, our design, shown in Fig. 9, seems similar. However, the level of interactions and autonomy is increased. The 3D rendering shows the usual sleeping bag, that is attached to the wall, and a simple flat foam pillow to protect the head of the astronaut while in sleep. It is also attached to the wall. Both the sleeping bag and the pillow are detachable from the wall. Either the pillow or the sleeping bag can incorporate a hood that shields the eyes during sleep. Inside the cabin there are other sensors to receive signals from the user, and equipment that can provide response signals. For example, as illustrated in Fig. 10, a microphone can listen to environmental noises, from both the equipment and human generated noises (e.g., snoring). Processing these through noise cancellation, the wall mounted speakers can provide a much quieter environment than it is today. The speakers can also play music or relaxation sounds. The microphone and speaker combination can support interactions with others or can be used for entertainment. Light fixtures and computer monitors can be used for light therapy, and used in connection with the vital signs of the user for relaxation and during sleep. The light frequency can also vary depending on the mood or if we want to replicate solar cycles. These types of environmental color adjustments are already used on airplanes. The use of aromas can augment relaxation exercises, but requires careful design and mitigation methods in a permanent closed small environment, such as a space habitat. The only element in this pillow system that provides physical contact with the user is the actual pillow. In zero gravity there is no need for head support, but it can protect the head of the user from bumping against the wall during sleep. Still, this physical contact allows for materiality considerations. The size of the pillow can be small, with a shallow depth, and a layered construction, discussed in Ref. [16]. A solid frame can be used as the attachment link between the pillow and the wall. However, an even simpler solution of a hook-and-loop fastener strip (e.g., VELCRO) might suffice. The long lasting soft or firm foam—based on astronaut preference—would make up the medium layer. The other layer would be designed to support physical touch, the same way as we use a pillow case. Design considerations for customization and personal preferences could include color, texture, smell, temperature, recyclability, cleaning, easy assembly and handling, in support of the wellbeing and physiological and psychological needs of the user. These approaches provide cross-coupling between multiple sensors in the habitat space, while stimulating the sensory perception of the user. Circular interactions between the users and their environment can mutually increase or decrease variety, driven by the situation or event. Autonomy can play an important role, where the system would learn user behavior, from sleeping to relaxation, and offer options to the user or act in a predictive or a supporting mode. Reconfigurability of the pillow system and in a broader sense the personal space would afford additional options for the user.

These designer interaction approaches need to account for other crew members inside the habitat. While the personal space provides some privacy, other factors, such as sound, smell may impact others around. While addressing higher-level needs, such as the wellbeing of the crew members, we still need to be cognisant of the basic needs in the design. Basic needs are addressed through the usual technological solutions.

4. Summary

Today's ISS crew quarters support the basic needs of the astronauts. Through this design exploration for a space pillow system, we attempted to initiate a conversation about boundary objects, in general, inside personal spaces for astronauts, that can cater to their higher level

Fig. 8. Scott Kelly's living quarters on the ISS [21]. It illustrates the "lived in" configuration of a personal space, with small personal touches and improvements compared to the mockup design shown in Fig. 1.

needs. With this, we attempted to exemplify how artistic and designerly processes can contribute to space exploration. Through artifacts—like the space pillow system discussed here—we can provide an emotional connection and bridge between the space travelers and their terrestrial home. We found that the interactions are more important than the actual artifacts, in this case, a pillow. We believe that the functionality and interaction between the astronauts and their environments can be further improved by also catering to their higher level needs on Maslow's HoN, through multi-sensory engagements on long duration spaceflight. Such boundary objects will have demonstrably positive benefits for the crew, from basic needs (psychological and physiological) to safety, as well as interactions, collaborations, playing, creating, and learning. Usability, built-in and curated autonomy, and aesthetics can enhance the utility of these objects. Autonomy—curated by

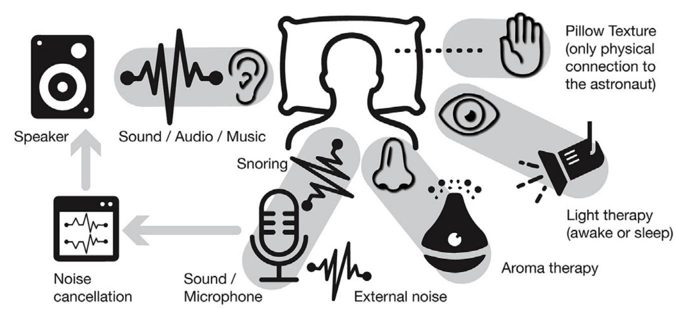

Fig. 10. Pillow concept with decoupled and augmented functionalities for the various sensory perception organs of the astronaut. The only object that has physical contact with the astronaut is the pillow.

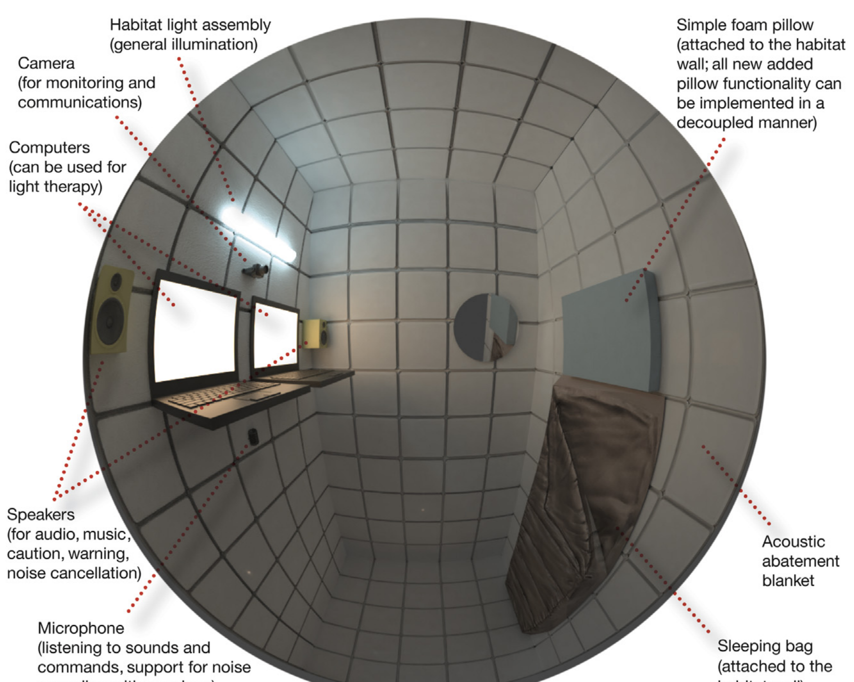

Fig. 9. Notional crew quarter with the pillow system, and its decoupled functionalities (modeled and rendered in Blender3d).

designers and artists— must allow for sufficient variety to promote exploration, learning, object evolution in line with second-order cybernetics and second-order boundary objects (These foundational topics are further detailed in Refs. [4,17].).

During this process we demonstrated a way to broaden our concepts to other artifacts inside space habitats with user interactions and curated autonomy in support of discovery, learning, relaxation, comfort and wellbeing.

By choosing a pillow as a focal point of this project, we hoped to engage artists, designers, and space architects to re-frame the discourse around space exploration, and to broaden today's technology-driven human space exploration paradigm.

5. Future work

Based on our research we can conclude that designing for the higher level needs of the crew benefits from the taxonomy framework, as it enables conversations between the various groups, including the users (crew), artist and designers, technologists, engineers and managers, who are typically responsible to designing the space habitats, as well as the users, the future crew members.

This taxonomy approach—over time—could develop into an ontological framework, which can be beneficial in identifying design guidelines and requirements.

Subsequently, a semantic ontology framework can support autonomy and automation, and can provide a context-based conversation between various entities.

In the next stage of this research we are focusing on evolving our trade space towards tangible ideas of other interactive and innovative artifacts envisioned for long duration space habitats, with a continuing focus on utilizing design and art practices for interactions in both closely coupled and decoupled configurations.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actaastro.2019.03.048.

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