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HOW TO DESIGN AND FLY YOUR HUMANLY SPACE OBJECT IN SPACE?

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Today's space exploration, both robotic- and human-exploration driven, is dominated by objects and artifacts which are mostly conceived, designed and built through technology and engineering approaches. They are functional, reliable, safe, and expensive. Building on considerations and concepts established in an earlier paper, we can state that the current approach leaves very little room for art and design based objects, as organizations—typically led by engineers, project and business managers— see the inclusion of these disciplines and artifacts as nice to have instead of a genuine need, let alone requirement. In this paper we will other initial discussions about where design and engineering practices are different or similar and how to bridge them. Highlight the benefits that domains such as design or art can other to space exploration. Some of the design considerations and approaches will be demonstrated through the double diamond of divergence-convergence cycles of design, leading to an experimental piece called a "cybernetic astronaut chair", which was designed as a form of abstraction and discussion point to highlight a subset of concepts and ideas that designers may consider when designing objects for space use, with attention to human-centered or humanly interactions. Although there are few suggested functional needs for chairs in space, they can provide reassuring emotional experiences from home, while being far away from home. In zero gravity, back-to-back seats provide affordances—or add variety in a cybernetic sense—to accommodate two astronauts simultaneously, while implying the circularity of cybernetics in a rather symbolic way. The cybernetic astronaut chair allows us to refine the three-actor model proposed in a previous paper, defining the circular interactions between the artist or designer; object or process; and user or observer. We will also dedicate a brief discussion to the process of navigating through the complex regulations of space agencies, from solicitations through development and testing, to space flight. The provided insights to designers and artists, related to agency-driven processes and requirements, may help to deconvolute the steps and may lead to flying their objects or artifacts in space.

I. INTRODUCTION

Over the past year our robotic missions continued to explore the solar system with rovers, landers, and spacecraft orbiting and flying by planetary destinations. These missions, as well as today's human exploration missions, are conceived by scientists, engineers, mission architects, technologists, and managers, through integrated thinking and systems engineering approaches. While human space exploration is still limited to the vicinity of Earth, we have plans to send humans to Mars within the next 20 to 30 years. All of today's space missions are driven by functionality, reliability and safety. They are also expensive, while set in a resource-limited environment, where funding represents a constant uphill battle. This environment focuses on fulfilling basic functional and physiological needs, while looks at psychological and self-fulfillment needs as nice to have, something that can be addressed towards the end of a flight project, if resources are available. Artists and human centered designers address such higher level needs, thus currently playing a limited role in our space exploration activities. However, we believe that these higher level needs should play increasingly important roles in our future space exploration plans. First, on near term missions to validate this approach, then implemented fully on subsequent long-duration human missions.

In our previous paper [BA15] we have introduced considerations for human centered designers and artists, who are creating for the space environment. The scale of these may range from a single artifact to fully immersive integrated systems, such as a habitat. We have discussed fundamental concepts that might be beneficial to designers and artist, including tacit knowledge, cognitive learning, cybernetics, and affordances. We introduced a three actor framework, consisting of the designer or artist, the observer (in this case an astronaut), and the object or artifact. We also provided contemporary examples from the fields of art and design to illustrate these underlying concepts. In [BA15+] we have extended this methodology to the roles of design and cybernetics for planetary probe missions, arguing that human centered design is not lim-

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ited to human exploration missions, and can be highly beneficial to aspects of robotic missions. This includes improved design dialogs between the project teams and their stakeholders, better communications with the public, and improved design environments.

In this paper we revisit and advance the list of artistic and design considerations for future space missions, including the roles of cybernetics, perception and cognition. We will illustrate aspects of these considerations through a physical artifact, a "cybernetic astronaut chair", which will serve as a discussion point. We will also outline approaches related to a human centered interactive habitat, advancing the current state of practice, which to date mainly focuses on fulfilling basic physiological and related functional needs. Finally, we will provide a brief introduction to agency-driven processes and requirements related to design considerations for space bound objects and artifacts. Better understanding of these processes could be beneficial for space artists and designers and help them to account for these additional requirements throughout their creative cycles.

II. FOUNDATIONAL CONCEPTS

Creating and conceiving artifacts involves at least three essential elements. First, a perspective that allows us to look at the world. It consists of a cognitive model of our environment and us in it. Second, an idea about what we wish to create, encompassing our motivations and goals. Third, a suitable process that includes creative thinking and making. This often-iterative process involves guiding choices to move us towards preferred outcomes.

In our earlier paper [BH15] we have introduced a three-actor model, describing the interactions between an artist/designer, the artifact/object, and the observer/user. These circular cybernetic connections between our environment and cognitive models lead to a constructivist middle ground between an actor (artist/designer or the observer/user) and the environment.

II.I Cybernetics, Perception, and Cognition

We built our approach on cybernetics, which is a transdisciplinary field, initially defined by Norbert Wiener in 1948, as the "Control and Communication in the Animal and the Machine" in his book with the same title [Wie48]. The origin of the word, cybernetics, traces back to the Greek word Kybernetike (κυβερνητική), in relations to governing, steering a ship, and navigating. Cyberneticians study — among others — a broad range of fields, including philosophy, epistemology, hierarchy, emergence, perception, cognition, learning, sociology, social interactions and control, communications, connectivity, mathematics, design, psychology, and management. Many of today's control and network systems associated disciplines, systems engineering, psychology and biology fields find their roots in cybernetics, and often associated with first-order cybernetics. Further advancements looked at the system that is observing the system, called second-order cybernetics. Artistic expressions often fall into this category, reflecting on our environment, experiences, social norms, and defining novel points of views. Subsequently, this allows us to create new languages and discourses through art and design, leading to new options, conclusions, and outcomes.

We can construct our cybernetic models through the reduction of complex observed systems to simple ones [Wei91], but we need to be aware that "essentially, all models are wrong, but some are useful" [BD87]. Thus, to draw meaningful conclusions from models, our simplifications have to capture and weight all the key influencing factors, and ignore those which have secondary effects on the modeled system. This modeling is not trivial and it applies to our processes of creating cognitive views of the world. Furthermore, the fidelity of these models vary between fitting or matching our observations. Simplifications may lead to loss of fidelity, and understanding what can be ignored can significantly impact the usefulness of the models.

Such constructivist approach is based on a philosophical view, which theorizes that all knowledge is constructed by humans, by coming to a common ground between the metaphysical world and our cognitive models of it. It requires participation, opposed to a rationalistic view where the world is observed and discovered neutrally and objectively. As knowledge can be described as justified true belief, Immanuel Kant pointed out that we need both empiricist experiences and rationalistic reasons [Kan81]. We need experiences to create our cognitive models, while creating a model without validation can only lead to theoretical illusions. Radical constructivism was introduced by Ernst von Glasersfeld [Gla01]. According to radical constructivist theory, knowledge is personal, and not transferable between people. Instead, new ideas and models are constructed by each individual, from external inputs, combined with personal knowledge. These emerging constructed models are influenced by a person's subjective interpretation of an experience, instead of an objective reality. This model forms a circular dialog, aligned with the principles of cybernetics. Following a constructivist or radical constructivist approach over other philosophical schools of thoughts is a personal choice, based on a subjective belief in this process. Through selectively choosing arguments it leads to constructing our own ontology, our personal knowing, and our own model of the metaphysical world.

Within the field of cybernetics, the term "variety" was introduced by W. Ross Ashby [Ash56], referring to the degrees of freedom of a system. For a stable system in

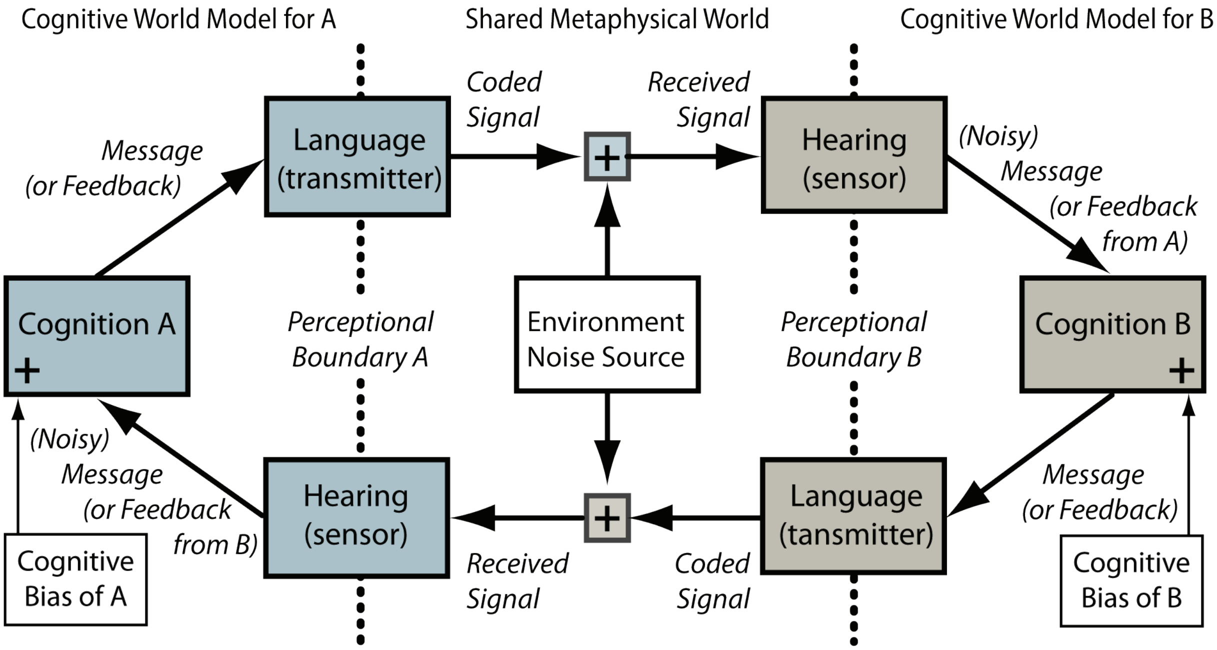


Fig. 1 Schematic diagram of a constructivist dialog between two actors, based on cybernetic circularity; also showing the perceptional boundary for each person.

dynamic equilibrium, its regulatory mechanism has to have greater or equal number of states than the environment or system it controls, as defined by the Law of Requisite Variety. Ashby states his Law as "variety absorbs variety, defines the minimum number of states necessary for a controller to control a system of a given number of states". This Law also relates to Claude Shannon's information theory, introduced in 1948 [Sha48]. It is dealing with "incessant fluctuations" or noise in the communication system, and can be applied to a broad range of disciplines from art and design to engineering and computer science. The model parses communication to eight piecewise components, which includes: the information source; the message; the transmitter; the signal; the carrier; the noise; the receiver; and the destination. This model can also be applied to human interactions, as shown in Figure 1, using language and related dialogs as a basis for communicating. For example, when Actor A poses a question, Actor B is trying to understand its meaning. The answer is based on Actor B's understanding of the question, which is subsequently interpreted by Actor B from the feedback. Environmental noise can interfere with the communication loops, and need to be filtered out by the actors. This circular dialog may continue until a constructed middle-ground understanding is reached between the two actors.

We can abstract this model further to cybernetic interactions from the perspective of one actor (the regulator). It then includes three elements: the system (or regulator); a process; and the environment, as shown in Figure 2. The regulator generates some change in its environment through the process in order to balance the overall variety. This change is then reflected through feedback that influences subsequent changes in the regulator. This circular causal interaction continues until a stopping criterion is reached. Hence cybernetics provides a way to look at things and focuses more on communications than control, but addresses them both in a circular way with forward and feedback loops. Cybernetics related considerations play important roles in introducing new dialogs to space exploration through art and design.

To create cognitive models of the metaphysical world, we first need to perceive it through our sensory organs (i.e., eyes for vision, nose for smell, ears for hearing, tongue for taste, skin for touch, and vestibular sensors for balance and movement). The information input, in the form of energy from the environment, passes through these bodily sensors, and translates into perceptional experiences by cognitive processes. This communication across perceptional boundaries is shown in Figure 3. The steps of this incoming information flow seems obvious, yet explaining particular details of perception and cognition occupied psychologists for a long time. The theory of cognition and human intelligence development was first constructed by Jean Piaget, a Swiss developmental psychologist [Pia52][SR96]. Piaget was also a constructivist, focusing on the cognitive developmental stage theory of children, including logic, language, space and time, and play, but also addressed knowledge acquisition, construction and use. He theorized that knowledge is developed

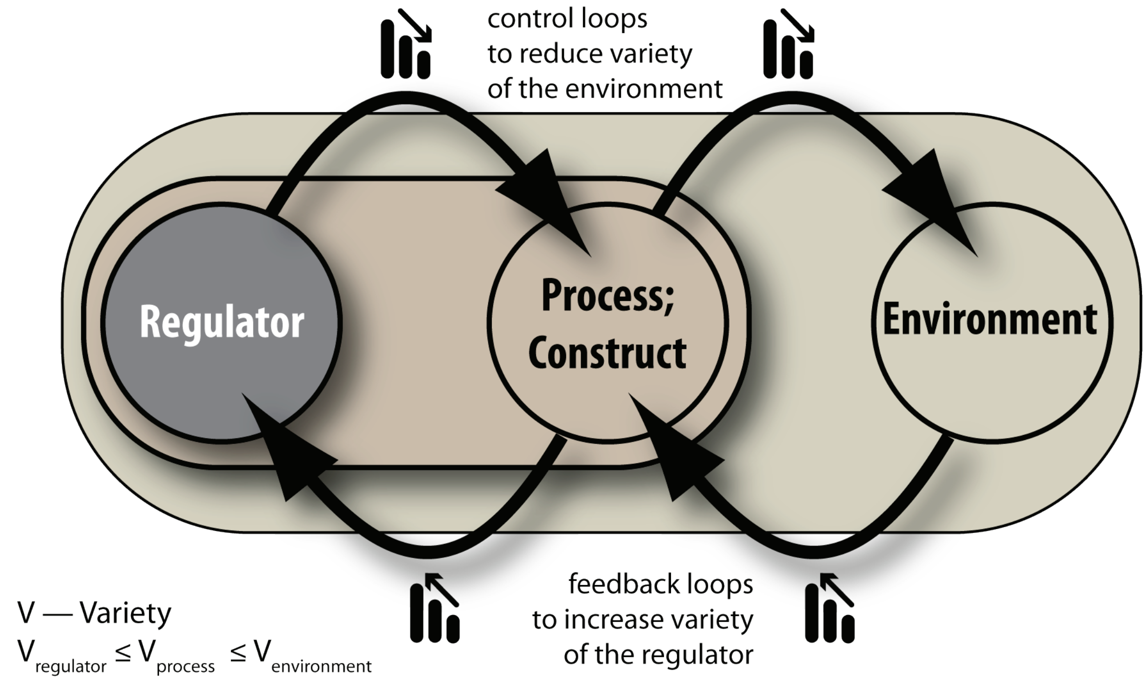


Fig. 2: Simplified model of a circular cybernetic loop.

gradually, in stages, and by constructing and understanding of the world through sensory experiences and interactions. Furthermore, alignments and discrepancies with building blocks of intelligent behavior and knowledge (schemata) influence interpretation and learning. Each of Piaget's schema provides a relational categorization of information about an aspect of the observed world [Pia52]. The sensory perception path follows three distinct yet interconnected elements: 1) the object itself; 2) the observer's sensory system; and 3) the mural pathways of the brain involved with sensory perception. Cognitive processes include perceiving, remembering, believing, reasoning. These steps may evoke emotions, which constantly intertwine with cognition. Interactions between the object and the observer are achieved through three complementary processes, namely assimilation, accommodation, and creating a new schema. In the case of assimilation, interaction with the object is approached through previous experiences of the observer, and if there is an alignment, then the new experience will become part of the existing schema. Accommodation requires revision of the old schema to fit the new experiences. When these two approaches do not work, the observer is required to create a new schema to interpret the new experience. The sequential process of assimilation, accommodation and creating a new schema is part of the process of experiencing and learning, and may evoke a range of emotions in the observer, including surprise, joy, and frustration. The circularity across perceptual boundaries (Figure 3) includes unidirectional incoming information from the environment through sensory perception; cognitive processing; and outgoing information through language (which may or may not be augmented with gestures or other means). This circularity completes a dialog loop, which is sequential, as the perceived information needs to be processed, then responded to (see Figure 1). The interpretation of the incoming signal is dependent on the cognitive model of the person, and may align with Piaget's three complementary processes. For the outgoing signal, language is used to communicate meaning, representing the condition of realness (e.g., Is this carp a fish? Yes, it is.), and falsehood (e.g., Is this dolphin a fish? No, it is a mammal.). Meaning is defined by its truth-value, but also by its use-value. Truth condition theory was introduced by Wittgenstein early in his career [WRO07], stating that only a strict definition of the language is required to represent meaning. Later in his career he revised this position and introduced the use theory, where both the strict meaning of the language and the context are important. For example, making a sarcastic comment changes the strict meaning of a message. Therefore, when communicating, we need to account for both the truth and use conditions. Dialogs and interactions are further developed by Gordon Pask [Pas76] through his Conversation Theory. Pask considered any interaction with our environment as a conversation. We interpret our sensory input as part of the conversation and respond through our cognitive processes. Even if the process is internal, without the outgoing verbal message, it has the structure of a dialog with the environment. Designers and artists utilize these approaches of learning, interacting, dialoging with others or having a circular dialog with themselves, while creat-

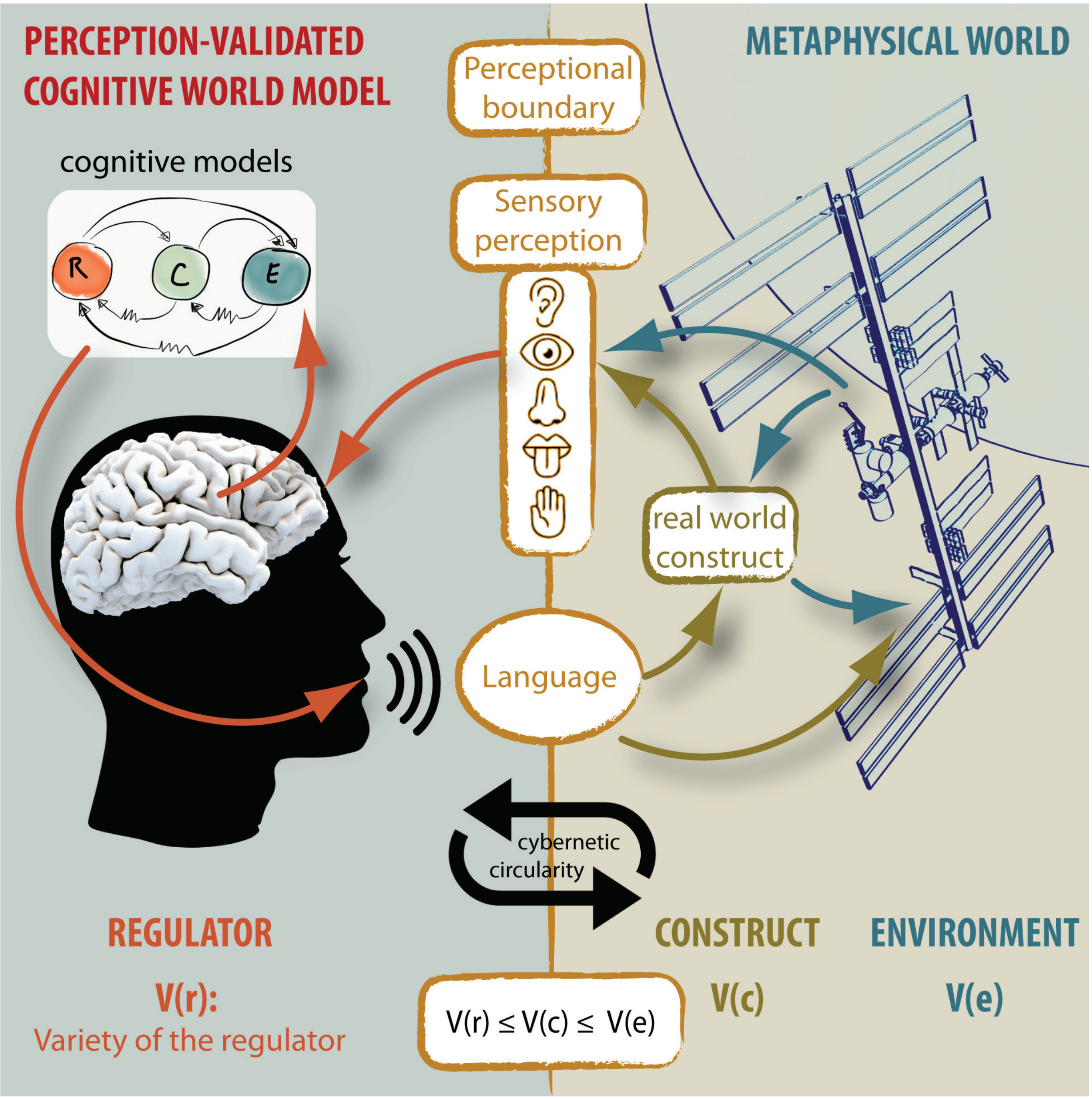


Fig. 3: Communication across perceptional boundaries.

ing through prototyping cycles. These activities are done either consciously or subconsciously, and subsequently built it into their artifacts.

One of the key considerations of perception and cognition is to identify if perception of our metaphysical world relies on a) information received directly through the bodily sensors, or b) if previous knowledge by the person and expectations also adds to the cognitive interpretation. James Gibson, the American psychologist, proposed a direct "bottom up" theory of perception [Gib66]. This approach is data driven, and linearly unidirectional through the visual processing, and it initiates with the sensory stimulus. In comparison, Richard Gregory, a British psychologist, proposed an indirect "top down" constructivist theory [Gre70]. It combines sensory and contextual information to recognize patterns. For example, in a noisy environment we may understand a word when included in a sentence more than the word alone, as our cognition can provide the appropriate filtering and interpretation. This is also a guessing process through the formulation of a perceptual hypothesis between the sensory input and our knowledge, as a word may have many meanings. Thus a priori knowledge can be very influential in the cognitive processes. In this constructivist approach there is a circularity between guessing cycles that refines our initial hypothesis on a meaning to a middle ground, where

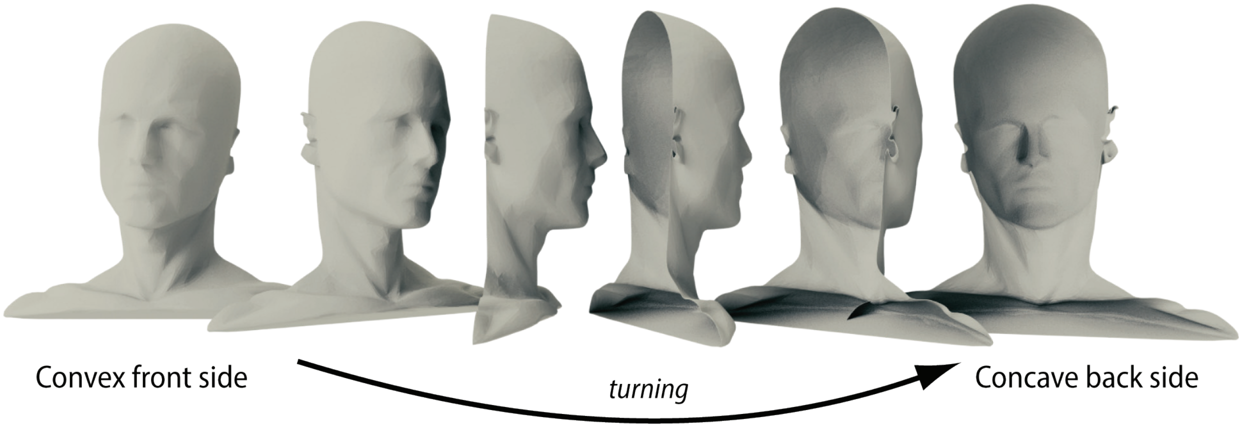


Fig. 4:Visual perception error with convex and concave face

our internal model aligns with the received information. Incorrect interpretation can lead to perception errors. A visual perception error example is the concave face illusion, shown in Figure 4, illustrates how our cognition interprets a concave face as convex, even though it is clearly shown otherwise. This “unconscious inference” is based on our previous experiences, supporting Gregory’s theory that the information is not simply based on direct input data. Gibson opposed Gregory’s top down approach arguing that Gregory’s examples are taken out of context, while a full sensory input provides sufficient environmental information to make sense of it, and to justify a data driven direct approach. He pointed to flow patterns, invariant features, and affordances [Gib77]. Flow patterns inform us about motion parallax, that is relative speed as a function of distance. Invariant feature refers to the different perceived size of the same object as a function of distance. Affordances are interaction possibilities between a person and objects. Yet, Gibson’s theory doesn’t account for perception errors (Figure 4), or naturally occurring illusions, for example looking at stationary objects out of a train’s window, which appears as the train starts to move, while the fixed environment with the observer and the train cabin feels stationary. None of these two theories can explain all of the perceptional experiences under all circumstances. To resolve this impasse, Ulric Neisser proposed a model, he called it a “perceptual cycle”, where the top down and bottom up processes work in a circular way (see Figure 5) [Nei76]. He pointed out that purely data driven approach would make people mindless robots, while a purely prior knowledge driven approach would make them dreamers without physical grounding. (This combined approach is reminiscent of Kant’s philosophical work, where he pointed out the need for both rationalistic and empiricist approaches.) Thus, in a circular process our cognitive models (or schemata) provide expectations (hypothesis) for given contexts. If the sensory input disagrees with this hypothesis, then it does not fit an existing schema, and in line with Piaget’s approach the schema is either extended, or a new schema is created for a new experience.

II.II Art, Design, and Dialogs

Bruce Archer categorization grouped anthropocentric activities into Science, Humanities, and a third discipline, Design with a capital D [Arc78]. He placed scientists into the Science category, while putting artists, designers, engineers, and other practitioners who create novel parts, into the Design category. Archer’s categorization of science describes the metaphysical world of natural laws to be independent from humanity. In the empirical tradition of Hume [Hum39], its exploration is done through controlled experiments, classifications, and

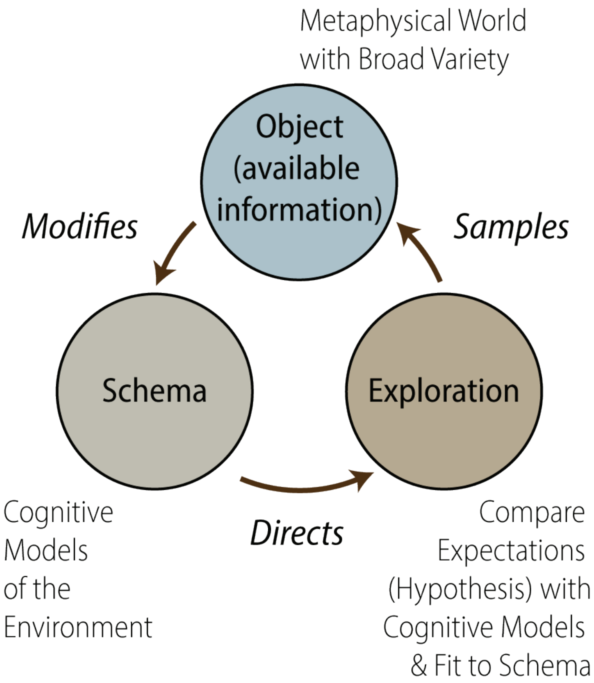


Fig. 5: Perceptual cycle of perception and cognition (augmented from Neisser [Nei76])

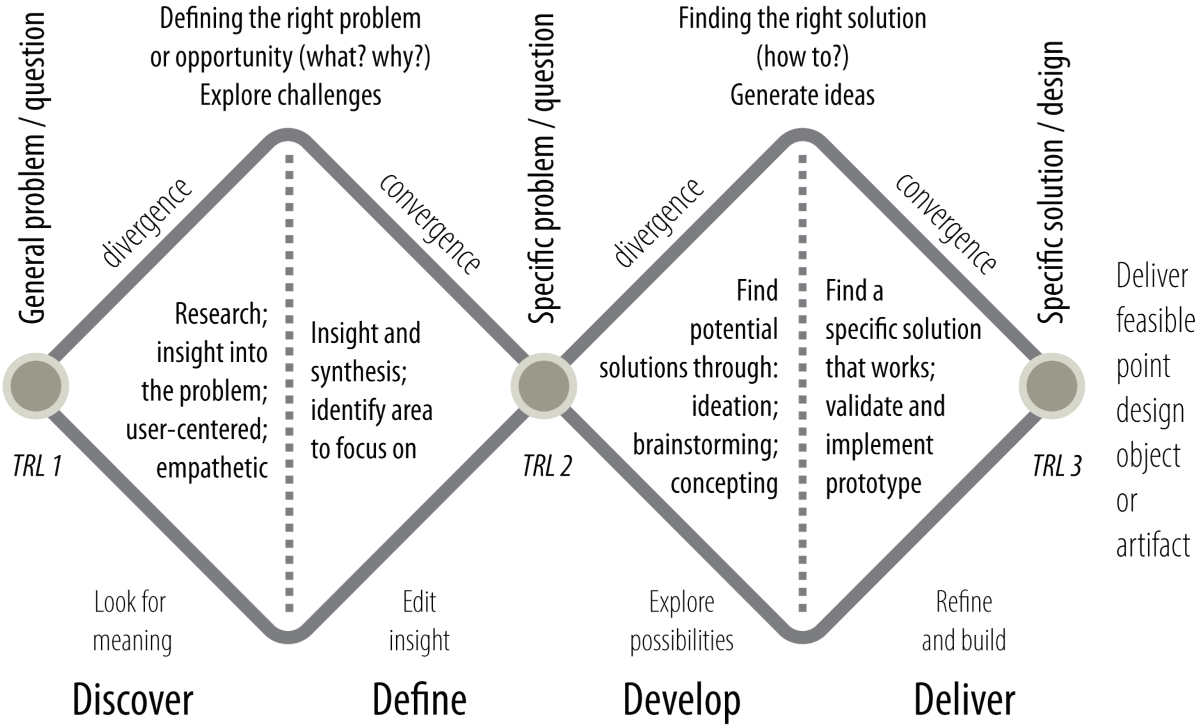


Fig. 6: Double diamond of design with approximate Technology Readiness Level matching

analysis of its sub-disciplines. It is an objective and rational approach that is concerned with how things are, and with uncovering the "truth" through empirical methods. Humanities explore the human experience through evaluations, reflections, analogies, and metaphors, and it is concerned with justice, commitments, and subjectivity from an anthropocentric point of view. Design requires an active participation by humans, and it is concerned with the artificial world, creating the new, through pattern-formation, modeling, and synthesis, through practical and innovative ways. It focuses on appropriateness, empathy, and other humanly design considerations about how things ought to be. It introduces novel options and forms. Furthermore, Design is a non-linear discipline [HC09], where in a cybernetic sense the feedback broadens the regulator's understanding and knowledge (variety [Ash56]) allowing the designer to identify new previously unseen options from an added humanly perspective. In comparison, engineers typically take the initial requirements as bounding rules, and linearly converge towards a point design solution. These lines are often blurred within NASA, as science instruments are designed between the overlapping disciplines between science and engineering, designed by subject matter experts, who are well versed in both specialized fields. Artists and designers can also overlap between these categories. For example, creating new processes or materials can bring together art and design with material sciences. Reflecting or artistic activities may combine the Design category with Humanities. These lines and connections are often overlapping, but the importance of Archer's categorization is to identify a distinction and to show why creative disciplines are different from Science and Humanities.

Artifacts created by space artists are designers are unique and typically made only once or created for a single performance. However, space missions represent many constraints, hence pure artistic considerations will likely not lead to the selection or the flight of their projects. To overcome this issue, familiarity with design methods, Design Thinking, technology focused terminologies, and NASA processes, could play important roles. Looking at design methods, Figure 6 shows a double diamond visual representation of the design process. It is used to address two key questions. The first phase is used to define the right problem or opportunity, and in the second phase is set out to find the right solution. Both phases include a divergence stage, to identify and create options, and a second convergence stage to make choices. The process starts with posing a question. In the first phase an exploration is being carried out to find insights into the question, discover the meaning of the posed problem, then the identified options are synthesized to define a specific problem or question. In the second phase a potential solution-space is developed through ideation, brainstorming, conception or other means. From these generated ideas a specific solution or design is selected, and validated through a prototype (e.g., breadboard, brassboard). This process is best suited to an early development stage, from Technology Readiness Level (TRL) 1 to 3 [Man95], where feasibility needs to be proven. Design Thinking requires learning by making and building in order to think. In effect it often builds on tacit knowledge [Pol66], which uses prototypes to speed up the process of innovations, because creating them will allow the practitioner to understand the strengths and weaknesses of the artifact or process being designed. This strategy starts with a human centered approach, balancing and harmonizing desirability or usability, with technical feasibility, and economic viability.

If Design Thinking is introduced at NASA, it should include designers and artists along with engineers, technologists, and scientists, in the early stages of the process. This is expected to introduce more creativity, beyond the purely analytical approaches. It would also help to “deep dive” into stakeholder needs, through discussions and observations. But there are insufficiencies with a Design Thinking approach, and it should be broadened to Design Dialogs. A design methodology should incorporate cybernetics to the prototyping phase, with strong considerations for the Law of Requisite Variety. Iterative cybernetic feedback loops would enhance the variety of the designer or artist, who could make better choices in subsequent iterations, with a set-out goal to benefit the users or observers.

In line with the three actor model [BH15], the artist or designer would first create the artifact through a circular dialog, exploring the possibilities through a divergent phase, then converging to a final outcome. In a subsequent phase the user would interact with the artifact through a separate spatially and temporally decoupled dialog, while observing, using and interacting with it. As the user’s variety is different from the designer’s variety, the interpretation of the artifact may differ from the intended use. Artist and designers could limit the variety of the object, narrowing its potential use to only the intended ones, and employ signifiers [Nor13] to highlight their potential use during the interactions. These clues are part of the dialog between the user and the artifact, and in a decoupled way between the artist or designer and the user.

Artist and designers create new languages, which emerge from Design Dialogs, which might be external or internal. These new languages then lead to new options and outcomes. Through the artifacts, artist and designers can broaden the variety of the users and observers, creating novel experiences beyond today’s function driven objects and artifacts.

III. DESIGNING A HUMANLY SPACE OBJECT

In the near future we could design humanly objects and artifacts for space missions, which need to operate in the extreme environments of space, including vacuum, extreme temperatures, planetary atmospheres, radiation, and low gravity. Using objects in a closed habitat requires safety considerations as well. Beyond the strictly physiological and safety needs, they could also provide support for psychological needs, such as love and belonging. These humanly objects can be designed and created on Earth or in space, and may target one or multiple senses from our sensory perception. Depending on the intended use or designed impact on the observer or user, the sensory stimuli could be coherent or not. Furthermore, on long-duration spaceflight resources are limited, therefore the object could be designed with multiple functions for diverse habitation scenarios, such as working, resting, exercising, and socializing.

The level of interactions between the astronauts and the artifacts may vary from passive observation to full interactivity. The types and levels of interactions with the objects are designed into them in the form of affordances [Gib77], and highlighted using signifiers [Nor13]. Since the variety of the environment is broader than that of the designer (regulator), the user of the object may find new unintended uses for the object, beyond the affordances conceived by the designer. This can be explained through cybernetic dialogs, and cross-referenced with the three-actor model presented in [BH15]. The first dialog happens between the designer and the object or artifact, as shown in Figure 7. Here the designer or artist (regulator) balances variety across the whole system through prototyping cycles. Such personal dialogs with the artifact may create new ideas that advance the design towards a final outcome. For example, when we create a prototype, it represents our cognitive output at that given time. It becomes a representation of our ideas, translated into a real world object. Through the prototyping steps the artifact also contains additional information, which may come from manufacturing or material imperfections, and its interactions with he environment. When we revisit this artifact in a subsequent iteration step, we may see it in a different light, which can provoke new ideas, thus broadening our own variety. This broadened variety from the perceptional feedback through subsequent iterations allows us to create new ideas and solutions, and reformulate our cognitive models or schema about the object. (It should be noted that the external noise from the environment has a cognitive internal counterpart, called cognitive bias [Kah13], which may find its roots in culture, or in the person’s cognitive inherent models, e.g., rigid ways of linear thinking. Cognitive bias can lead to an epistemological block [Til84], making changes difficult or at time impossible without new information—or in a cybernetic sense, by increasing the regulator’s variety.) The circular dialog between the artist or designer and the artifact or object continues until a stopping rule is applied during this convergence phase of the creative process. At this point the artifact/object is finalized. In a cybernetic

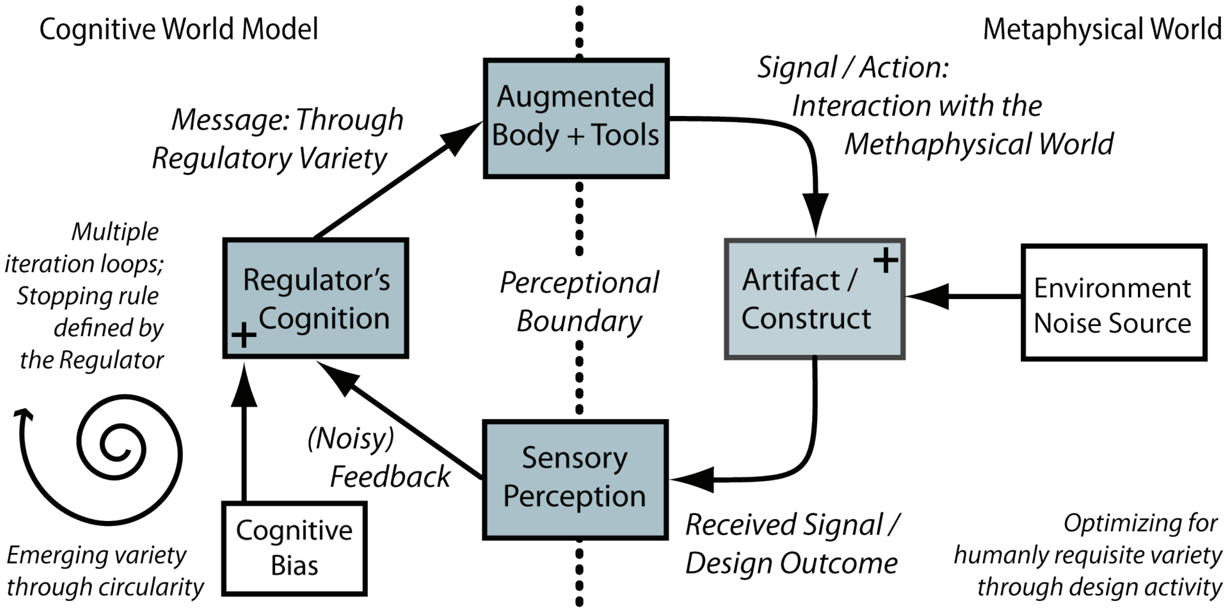


Fig. 7: Schematic diagram of a constructivist dialog between a designer/artist and his/her artifact or construct, based on cybernetic circularity; also showing the designer's perceptional boundary and cognitive bias.

sense, with the concluding artifact the artist, acting as a regulator, successfully balanced the variety and reached a perceived equilibrium between all elements of the system. These iterative dialogs are essential in the creative process. The second cybernetic design dialog takes place between the object or artifact and the observer or user, who now becomes the regulator of this system that includes also the environment in which they reside.

In our previous paper on humanly space objects [BH15], we have identified a number of considerations when designing for the space environment. We have slightly expanded this list and grouped them into categories, related to design aspects; arts; architecture; and engineering and technology. These considerations, shown below, may also overlap between multiple categories.

- *Design aspects:*
  - Affordances and signifiers
  - Emotional design and empathy with the object;
  - Temporal and spatial dimensions
  - Immersive awareness
  - Cultural aspects
  - Interactions (peer-to-peer; regulator versus environment; 3-actor model)
  - Human centered; human connections (emotional, physical)
  - Multi-level storytelling (knowledge transfer; emotional)
  - Scaled multi-level experiences
  - Cybernetic learning/teaching cycles
  - Relativistic interactions (changing roles)
  - Physical interactions
- *Artistic aspects:*
  - Abstraction
  - Changing the meaning
  - Certainty versus uncertainty (predictability)
  - Movement versus stillness
  - Visual impacts of light and dark
- *Architecture:*
  - Space habitats (scale, immersion, interaction)
- *Engineering and Technology:*
  - Mass and volume considerations
  - Safety considerations;
  - Spaceflight environment / extreme environment;
- *Combined attributes*

We are only listing these here in a bulletized form, as a reminder. Further details and discussions on them are provided in [BH15]. A subset of these considerations was used while designing the cybernetic astronaut chair, which will be outlined next.

III.I Cybernetic Astronaut Chair

In this subsection we discuss design considerations and circular design dialoging between the primary author of this paper and an his example object, called a "cybernetic astronaut chair". The design process was initiated through an exploration of the following general question: "*What type of artifact can be designed that addresses*

Fig. 8: Chair concept from the first iteration cycle (a) to (c); and the second iteration cycle (d) to (f)

a significant number of design considerations listed in [BH15]?" Through an initial set of divergence—convergence phase, and in accordance with the process shown in Figure 6, this general question was answered by identifying a number of potential ideas, then narrowing it down to a single specific question. The set of options ranged from static, dynamic, and interactive objects at different scales, up to a full habitat, from which a chair was chosen as a design object. The second convergence—divergence cycle explored various options for the chair design, which included sketching and computer modeling. From these options a final point design was chosen and built. In this discussion we will focus on the second design cycle.

The chair was designed and developed as a form of abstraction and discussion focal to highlight a subset of concepts and ideas that designers may consider when designing objects for space use, with attention to human-centeredness or humanly interactions. Although there is

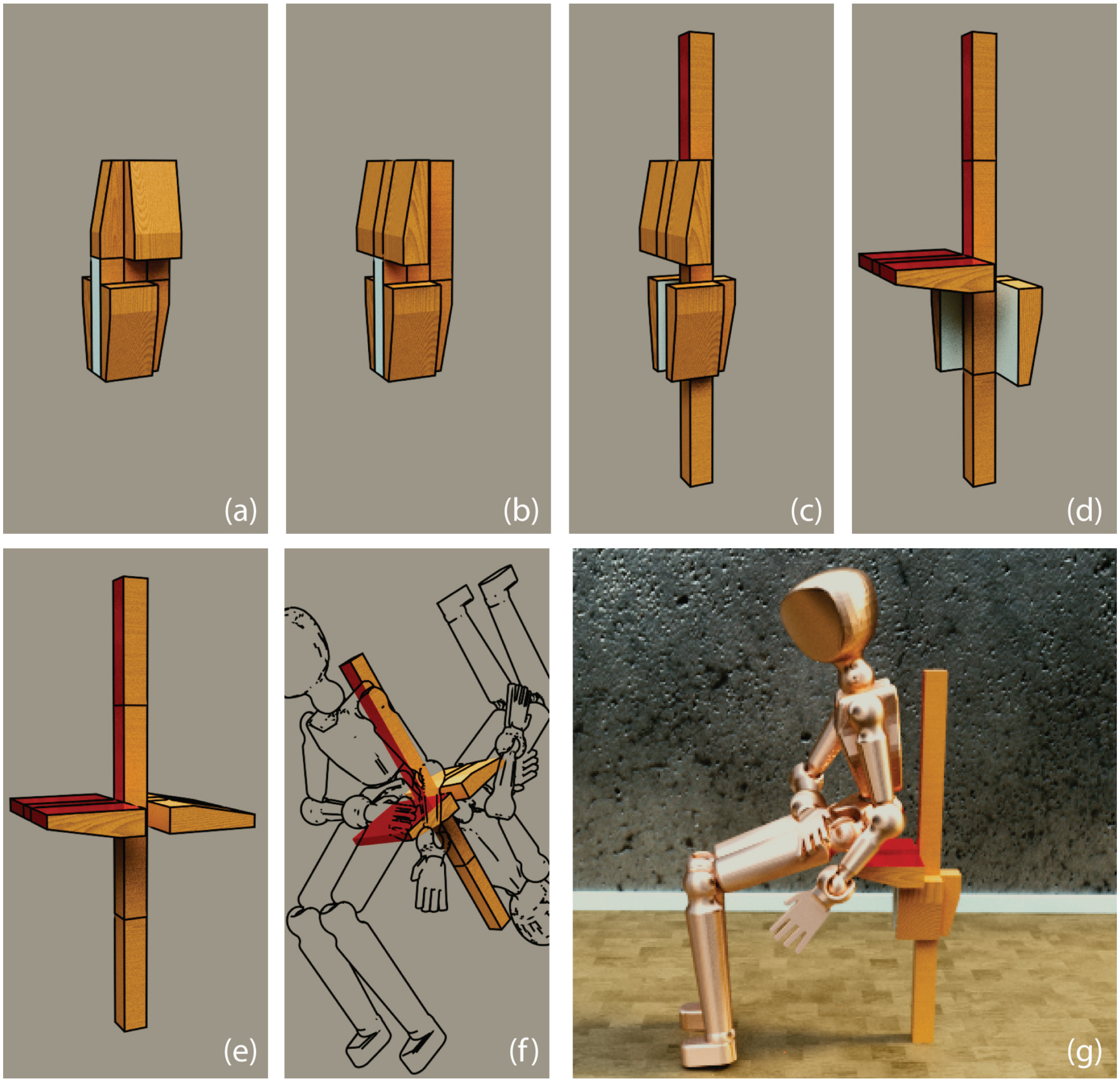


Fig. 9: Chair concept from the third iteration cycle

no functional need for chairs in space, they can provide the familiar and emotional experience of home, while far away from home. One of the key aspects of the design is the utilization of zero gravity, where up or down has no meaning or relevance. Consequently, the overarching theme between the various concepts was the use of two seating surfaces, attached back to back, which could accommodate two astronauts simultaneously, also symbolizing the circularity of cybernetics.

The first concept, shown in Figure 8 (a) to (c), was a relatively traditional looking chair with two seats back-to-back, on the top of each other. This compact design, rendered with the software Blender3D, was imagined with wooden or wired seats and a slightly tilted seating angle for comfort. With simple and familiar forms it evoked the feeling of comfort, but beside the implied cybernetic circularity of the seating arrangement and the need of zero gravity to use it by two people simultaneously, it didn't not provide additional connections to space.

The second family of the chair designs is shown if Figure 8 (d) to (f). Here the form was obstructed to the two seating and back support areas only. Refinements from Figure 8 (d) included further simplifications by taking out the middle truss of the back seats, thus reducing the mass, as shown in Figure 8 (e), and adding a seating angle for better support in Figure 8 (f). These designs were more compact and lighter than the ones shown in the fist set. The seating and back support areas were painted red on one side and white on the other, acting as signifiers for the two users. However, it was still a large and rigid construction, and the seating angle in (f) provided more of an aesthetic appeal than a real functionality, as in zero gravity such angles have no relevance or meaning.

The third iteration, shown in Figure 9, carried forward the abstraction and signifiers from the second set, with an added foldability feature and further simplifications. The unfolding process is shown in Figures 9 (a) to (e), while (f) and (g) provide information on how the chair could be used by two people or one person. This set provide a number of considerations from the list above. These include: compact stowage (relevant during launch, and storage and use inside a space habitat); light weight; safe use; size compatibility with a space habitat, physical connection with the user; abstraction; affordances to sit on; signifiers; and change in spatial dimensions during deployment. However, even from the designer's perspective it did not provide comfort for the intended users. Also, the form was abstracted too far, prompting the search for a new design direction, while building on the insights from these three iteration cycles.

The final design was inspired by the tensegrity robotics work at the Intelligent Robotics Group at NASA's Ames Research Center, in collaboration with a number of international universities [CDI+14]. The term tensegrity refers to tensional integrity, where the components, such as trusses, are isolated and under constant compression, provided by continuous tension from connecting cables. These are jointless structures, resulting in light yet sturdy and rigid frames. The referenced potential application for space robotics provided a connection between a space theme and the cybernetic astronaut chair.

To experiment with feasible tensegrity configurations, a tensegrity toolkit was created using wooden bars with holes, hooks and rubber bands. From the experimentation emerged a proto-tensegrity chair design, which is shown in Figure 10 (a).

The intended affordances for two simultaneous users in zero gravity is shown as a rendered sketch in Figure 10 (b). The seats provide affordances for sitting, while the cross below each seat—in the form of wires next to the feet—remove affordances, making that segment of the structure non-supportive for seating. (These wires were also needed for structural integrity.) In a cybernetic sense, the canvas seats increase variety of the object, while the cross–wires remove variety and enforce the intended seating orientations.

The next step was to build a full size mockup and to create the seating surfaces out of canvas (see Figure 11 (a) and (b). For the frame, five 1-meter long chrome plated metal tubes were used, where the temporary wooden end caps were tensioned with nylon strings. The final end caps were created with wood-dowel filled black PVC tubes, with the same diameter as the metal tubes. This was based on aesthetic considerations. The canvas for the seating area provided comfort, a familiar connection with the user, and easy stowage when folded up. The canvas sheets included several signifiers. The seating areas had three eyelids on each side of the sitting surface section, while only two per side on the back support section. To differentiate between the two user sides, the eyelids on one canvas was black, connecting to the frame trusses with black parachute cords, and silver on the other, connected with white parachute cords. The parachute

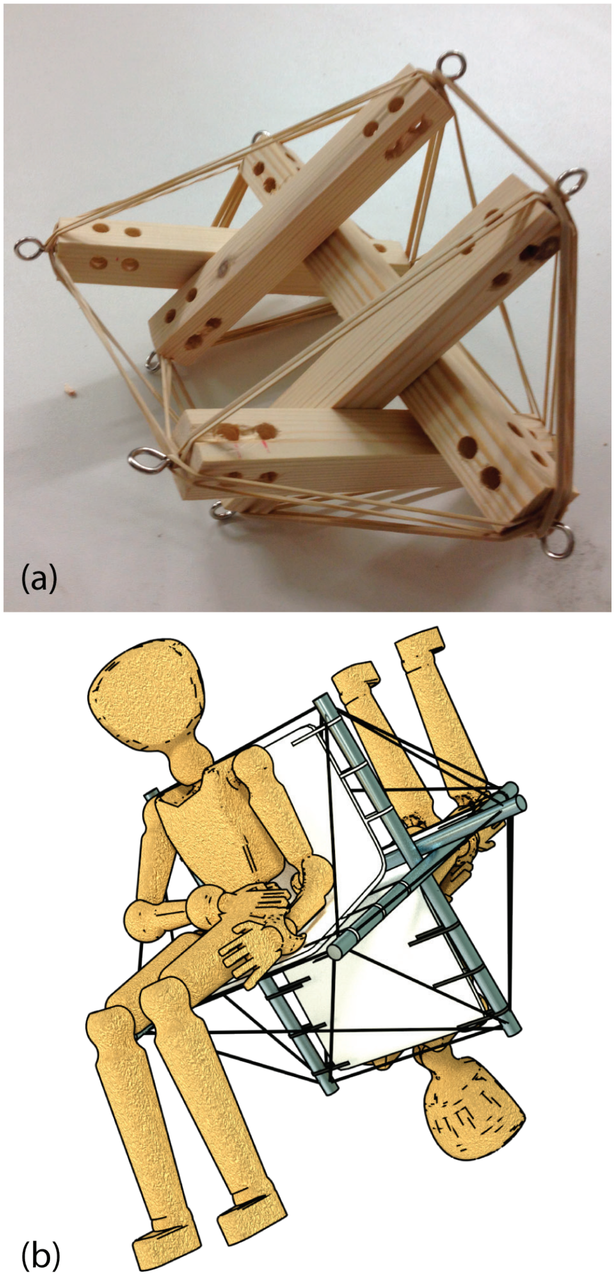


Fig. 10: Final design iteration: (a) tensegrity toolkit to experiment with the feasibility of various configurations; (b) 3D rendering of the intended use of the chair by two people in zero gravity

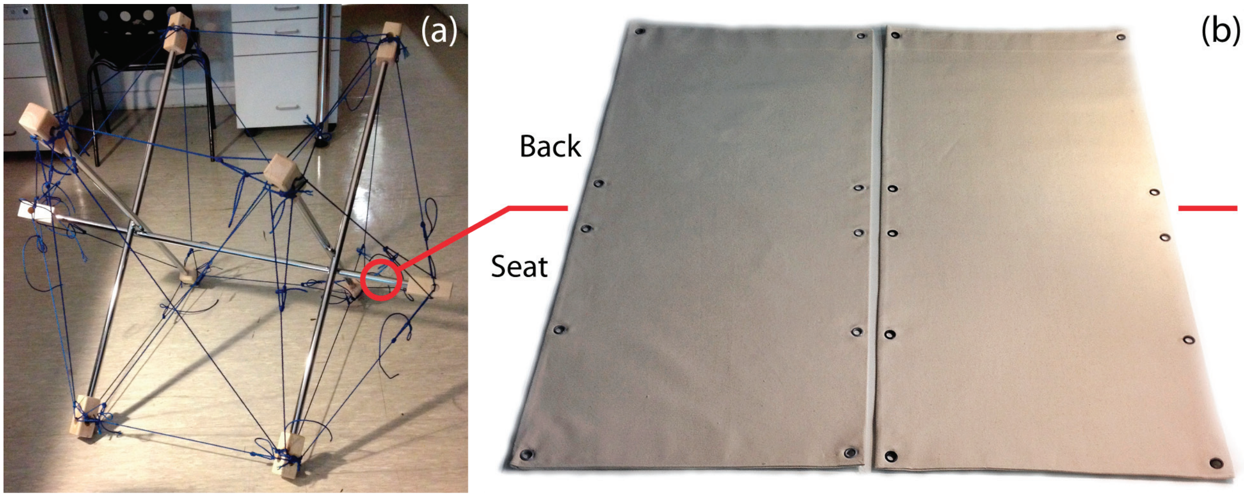


Fig. 11: (a) full size chair mockup with wooden end caps and nylon strings; (b) two canvas seats

cords, called paracords, were chose for their high tension strength and low elasticity, both of which are important for tensegrity structures.

The tensegrity structure—held together by wire tension alone—is light, with an total chair mass under 2kg, including all of its components. These components included five 1m long metal tubes with a 20mm external diameter; two folded canvas seats with 10 eyelids each; 25m of parachute cords, ten wooden and PVC end-caps; and 20 turn buckles. While the assembled chair had a bounding geometry of 1m by 0.7m by 0.7m, the disassembled parts could be stowed as a small volume during the flight to space. As an additional design feature, the parts can be reused and repurposed to change the meaning of the object. The assembly/disassembly also changes the temporal and spatial dimensions of this artifact. Safe-

Fig. 12: Front view of the cybernetic astronaut chair

Fig. 13: Side view of the chair highlighting its lightness and the expected small volume requirement when disassembled

Fig. 14: Close-up of the frame, seating area, eyelids, and the connecting cords

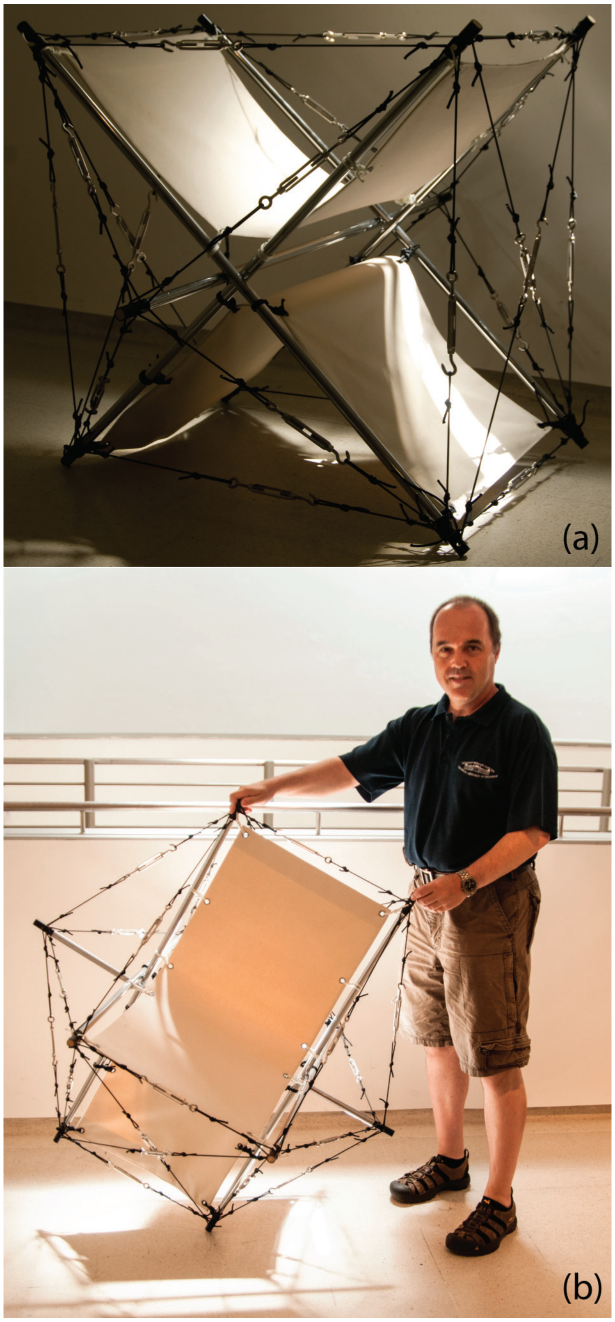


Fig. 15: (a) perspective view of the chair; and (b) the chair with the designer to demonstrate the scale

ty considerations are addressed through smooth surfaces, round edges, soft textiles, and light parachute cords. As a closing point, the "IKEA-like" assembly and disassembly activity of the chair can provide an enjoyable activity for astronauts, and break the monotony of long-duration spaceflight. The final chair design is shown in Figure 12 for a front view, Figure 13 for a side view, and Figure 14 for a close-up. Figure 15 (a) provides a perspective view of the chair, and Figure 15 (b) and angled view with the designer for scale.

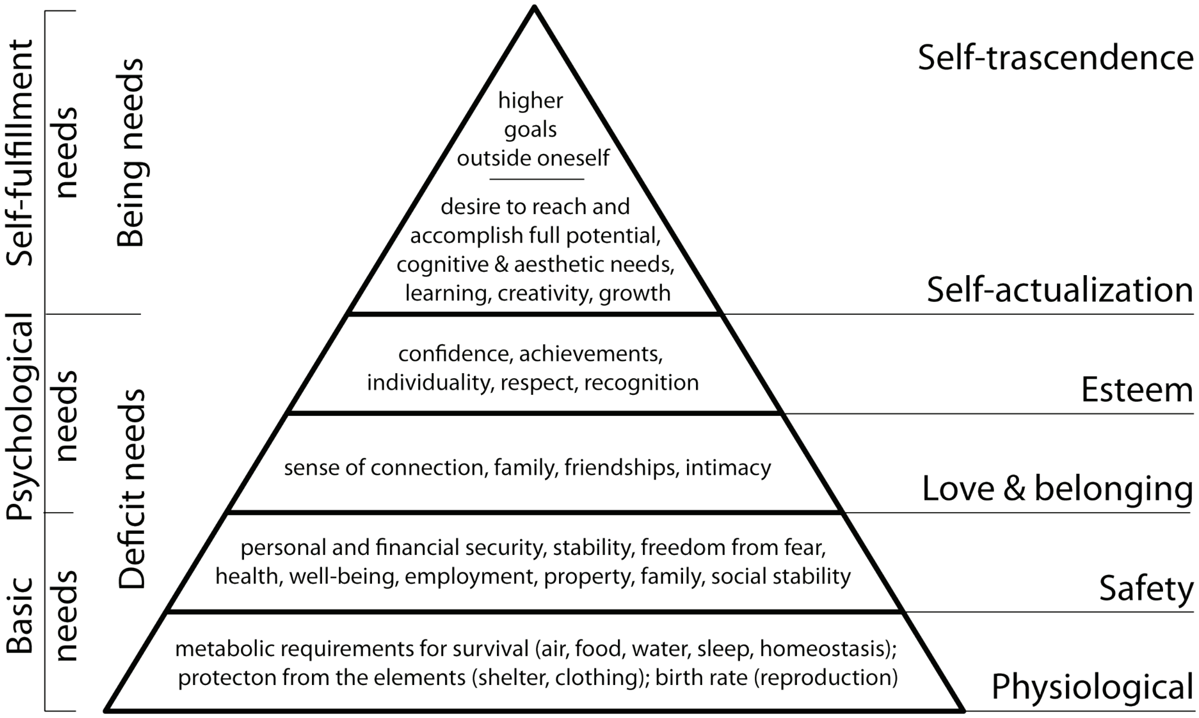
III.II Humanly Space Habitats

We now broaden the perspective from a single static artifact to the design of the full interactive space habitat, and provide a brief discussion through the lens of cybernetics based human centered design. This description provides and introduction to future research directions, and will be fully explored over the next year.

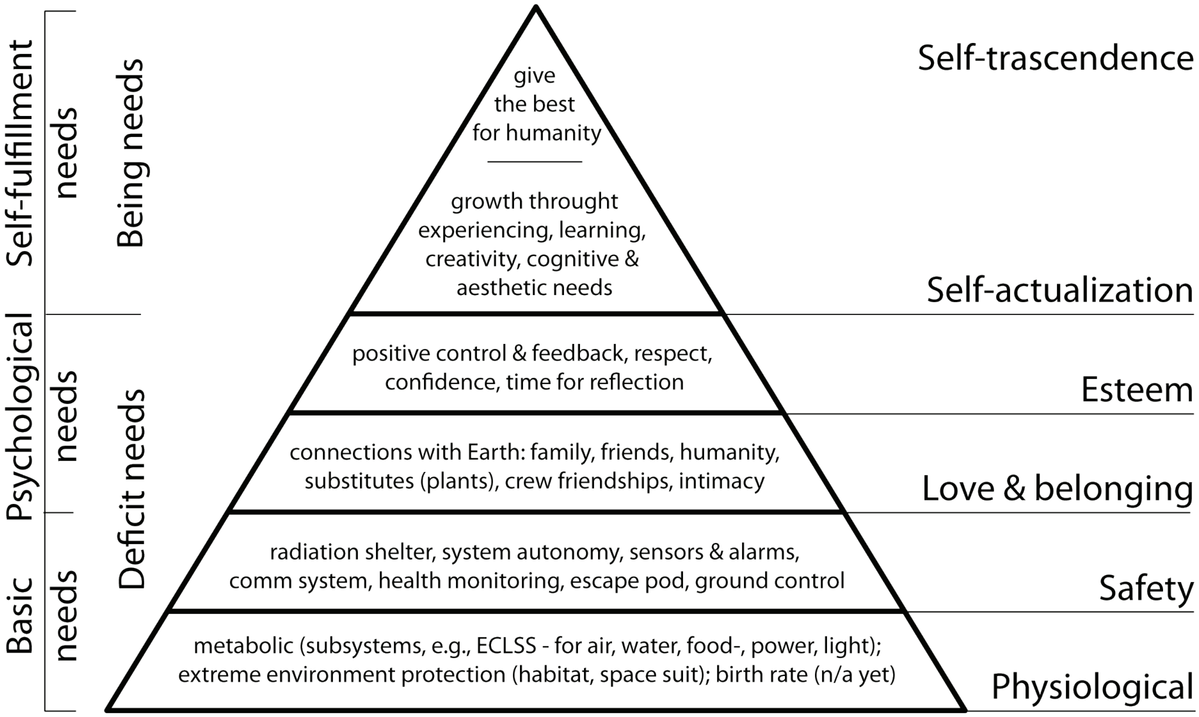
Human centered architecture that builds on cybernetic considerations was strongly advocated by Gordon Pask [Haq07]. His ideas are also applicable to humanly space habitats, making the environment dynamic and interactive. In today's habitat design interactivity is only implemented in an engineering sense, where astronauts spend years to learn operational procedures, set in place by engineers, based on initial requirements to support humans as one of the elements of the overall system. This proved to be sufficient on short duration near-Earth spaceflight. Looking at Abraham Maslow's Hierarchy of Needs (HoN) in Figure 16 (a) [Mas43][McL07], we can state that today's technology driven habitat designs only address basic physiological and safety needs, and account for some of the higher level psychological needs through astronaut pre-selection, and astronaut training.

Even NASA's Mars Design Reference Architecture (DRA5) [NAS09] dedicates only a few pages to ergonomics and higher needs, with a caveat that it will be addressed at a later time. The rest of the thousand or so pages documents aspects of engineering, technology, mission architectures, and other resource requirements. To read more about the human element for these future missions, we need to look at other documents, including the "Human Integration Design Handbook" [NAS10]. While it addresses human ergonomics, perception, cognition, and habitat architecture related issues, it is still less human centered design, and more of an engineering and human performance related document. Even the title implies looking at humans as fuzzy elements in the system, which has to be mitigated, guided, managed, so it wouldn't interfere with technology and engineering.

Such purely engineering and resource driven habitat designs primarily account for technical functionality, life support, and safety. Today's engineering and resource driven trends are influenced by some of the barriers NASA faces, related to resource limitations and a risk averse culture [BS14]. This wasn't always the case. We may recall that during the Apollo era, in the late sixties and early seventies, NASA worked with Raymond Loewy, the British industrial designer [LS72]. Many of the ideas and concepts from his full size mockups fed forward to subsequent design, including the storage racks on the International Space Station. He looked at habitat designs from a human centered perspective, making the



(a) Maslow's Hierarchy of Needs (HoN)



(b) HoN as it relates to astronauts and space systems

Fig. 16: (a) Maslow's Hierarchy of Needs (HoN); (b) HoN as it relates to astronauts and space systems

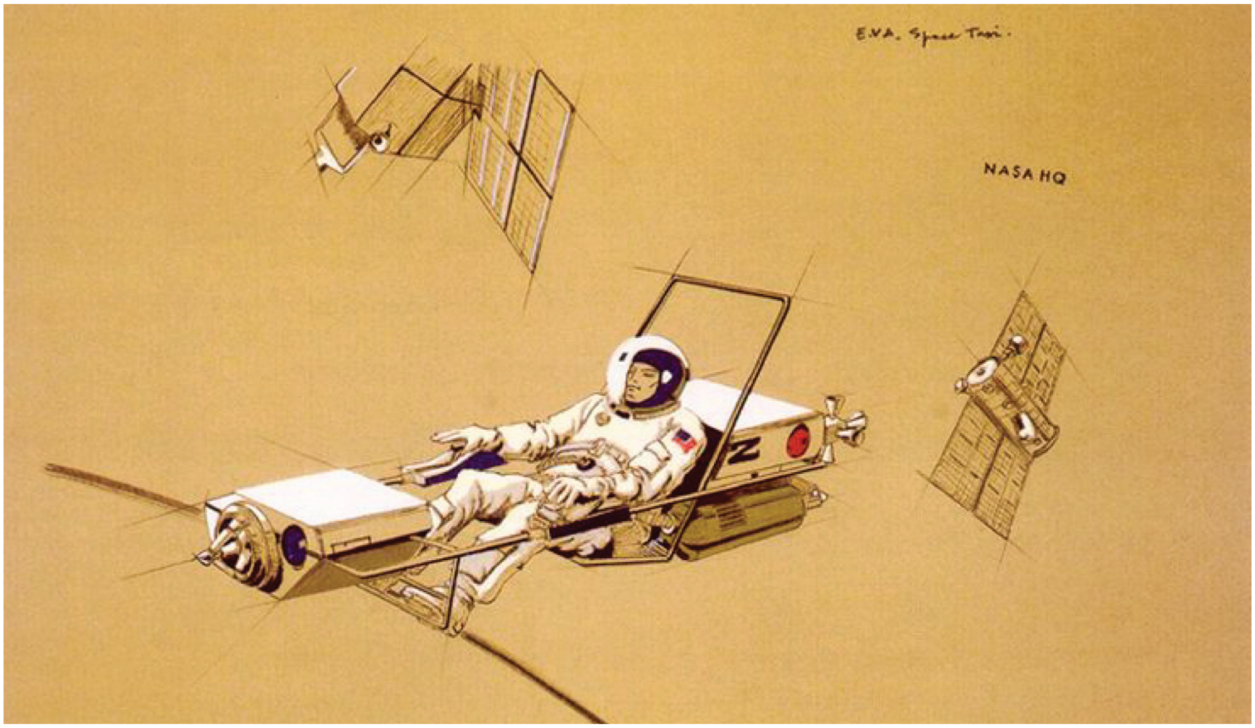


Fig. 17: Space taxi for NASA by Raymond Loewy (showing a different type of frame-based seating configuration)

environment more comfortable for the astronauts (see Figure 17).

In our view, today's space habitat designs predominantly cater towards basic needs, do not place high priority on human center design, and subsequently, not sufficiently equipped to support long-duration spaceflight. In today's designs, the limited habitat volume and pure functionality, combined with human physiological and psychological factors, would make the experience similar to a multi-years long solitary confinement. In Figure 16 (b) we mapped Maslow's HoN into relevant areas related to astronauts and support systems on space missions. To make a habitat design more human centered, Maslow's Hierarchy of Needs should be turned around, with a primary focus on the astronauts' higher level needs. The mandatory basic needs would be designed into the system through a subsequent step, and wrapped around the higher level needs. In effect, habitat designers would account for dynamic interactions between the astronaut and the environment, handing over control to the astronauts and to the habitat when possible, while removing as many of the predetermined control restrictions as practical. By providing dialog-based creative interactions with the environment across perceptional boundaries of the astronauts, the habitat could remove monotony during these long isolation inducing spaceflight. System responses would not be pre-defined by engineers prior to the mission, but instead, the system would be designed to construct its own input to the dialoguing in order to engage the astronauts, and foster harmonious relationships with other crew members and the habitat environment.

As a consequence, space habitats would become architectural systems instead of passive protective shells. Of course, this should be designed with care, and with the astronauts' safety in mind. It should be also noted that this approach would not negate the need to satisfy basic needs through technological means. But it would improve operational efficiency and psychological well-being, once the design is turned around and initiated with higher level needs, and better dialoguing.

This "Paskian architecture approach" would allow architects and designers to move beyond the current practice of providing architectural forms and nicer packaging, in line with basic functionality to address engineering and physiological needs. This could also involve artists to create artifacts for these long-duration space missions, and provide a dialog between their objects and the astronauts, while catering to their higher level needs of love, belonging, esteem and self-actualization.

IV FLYING A HUMANLY SPACE OBJECT

Part of the creative process for space-based art involves flying the artifacts in a relevant space environment. In the previous subsection we provided a discussion on creative perspectives for artists and designers, who wish to develop humanly space objects. Our goal is not to provide a step-by-step instruction manual on these processes, instead we will outline some considerations and point to resources, which can broaden understanding of space related project developments.

For this, we frame our discussion around the three areas of design thinking, namely desirability, feasibility, and viability. For a successful project all these areas need to be addressed and harmonized.

Desirability from NASA's perspective needs to address a programmatic relevance. NASA's 2014 Strategic Plan [NAS14] sets out strategic goals related to (1) expanding the frontiers of knowledge, capability, and opportunities in space; (2) advancing the understanding of Earth and developing technologies to improve the quality of life on our home planet; and (3) serving the American public and accomplishing NASA's Mission by effectively managing its workforce, technical capabilities, and infrastructure. Looking at these three goals, it seems that very little room is left for arts and design. Even a keyword search of the Strategic Plan for the words "art" and "arts" only found occurrences in the words "Earth" and "parts". Thus, the arts and design community must advocate for the benefits of artistic creativity is space beyond playing guitars and taking photos of the Earth, and make a case for NASA and to the other space agencies about societal benefits, benefits to the higher physiological and self fulfillment needs of the astronauts—for example on long-duration spaceflight—and benefits for the space agencies by providing an outreach opportunity that stimulates the interests of the public. A path toward raising awareness within space agencies could include work of space arts and design related advocacy groups, such IAF's Committee for the Cultural Utilisation of Space (ITACCUS) [ITA15], which includes advocacy, collaboration through meetings and workshops, maintaining communications and dialogs, creating a knowledge hub, and promoting high quality cultural products. From an agency's point of view, we may talk about art pull or push, referring to the direction of the development and infusion process, which is similar to the one used for technologies. NASA regularly releases solicitations on a broad range of topics through NSPIRES (NASA Solicitation and Proposal Integrated Review and Evaluation System). For example, NASA released an NRA (NASA Research Announcement) on the topic of ISS utilization, including higher education opportunities [NRA12]. These topics are well defined, and currently do not cover arts and design. Consequently, input from advocacy groups, such as ITACCUS, can impact the consideration of future topics to include arts and design. A different approach could involve unsolicited proposals to space agencies, which are outside of the solicitation cycles. Unsolicited proposals can have a number of outcomes after careful consideration by a space agency. If a strong argument is given for the benefits of the agency in line with its strategic goals, the proposal could be selected—based on funding availability—of the topic could be incorporated into a future solicitation, allowing other teams to compete for the award. This approach provides transparency of the selection process and ensures the highest quality projects to be selected.

Feasibility in the case of arts and design relates to the design consideration category for engineering and technology. Compliance with testing procedures and requirements play a significant role in the implementation process, which can make or break the project. For example, considerations by artists or designers should include minimizing the mass and volume to reduce resource requirements. Designing for the safety of the astronauts and the habitat when interacting with the artifacts may require the elimination of sharp edges, degassing of materials, mitigation of fire hazards, impact of decomposition due to time and radiation environment, fluid spillage in zero gravity and others, is depending on the nature of the artifact and its functionality. The objects also have to survive and operate in the extreme environment of space, including high g-loads and vibration during launch, zero gravity in orbit, extreme low temperatures, radiation, and additionally on planetary surfaces dust and abrasion, thermal cycling through diurnal cycles, just to name a few. During the project implementation phase the artifacts need to go through extensive testing to demonstrate compliance with these requirement. Therefore, the creative process is not complete without serious considerations for these requirement, and consultations with Subject Matter Experts (SMEs), starting at the initial ideation phase.

Resource and fiscal viability is a third key area that impacts a project. Specifically, how much will it cost, and who is going to fund it? In a resource constrained environment it is typical that projects are driven by functionality, followed only by form. Artistic objects do not fit into this framing, thus it is hard to argue on these points. Furthermore, space missions are very expensive, which creates additional difficulties for artists and designers. Thus, harmonizing viability with feasibility and desirability is the fist step towards addressing this challenge. The next step is to develop a details assessment of costs and resource requirements, which covers the full development lifecycle from ideation through development to launch and operations. Having this understanding and communicating it to NASA through solicitations or unsolicited proposals is a requirement to even initiate a dialog. If the project is solicited by NASA, the funding level will be identified for each award. That is cross-referenced against the budget submitted by the proposers, and evaluated for fidelity and scope. Other avenues to find the right funding could be based on angel investors who believe in the project and for their own motivation willing to invest into it, or using crowdsourcing, such as Kickstarter. Launching through private companies and using own funding could greatly simplify the process and logistics, but the payload still needs to go through appropriate testing and comply with regulations. It is safe to say that finding solutions to the viability issue is key to the success of any flight project.

In conclusion, further to creative approaches and processes, it is important to be aware of the special space environment, and NASA procedures and requirements. We hope that the provided insights may help to deconvolute the necessary steps and may lead to flying future objects or artifacts in space.

V. CONCLUSIONS

In this paper we have discussed creative considerations for artists and designers planning to design humanly space objects. These are objects which would be observed or used in the space environment. We built on the findings from our previous paper on the same topic, which included a 3-actor model with an artist/designer, an object, and a observer/user [BH15]. We advanced this model using cybernetics and design considerations, with a focus on human centered design and design dialogs. In this model cybernetics provides a perspective on our environment, which also include artifacts, objects, processes and regulators, who in our case are the artists and designers. Connections, design considerations and design dialogs between elements of this dynamic system provide guidance for artists and designers, allowing them to balance the variety across the overall system towards a preferred outcome. We have expanded and categorized design considerations for space objects and artifacts, and developed a physical object, a cybernetic astronaut chair, to translate these concepts into practice.

This final concept was derived through multiple divergence and convergence cycles; iterative design dialogs between the designer and the prototypes; and dialogs with other RCA IDE researchers and tutors. In each iteration and resulting prototype, these dialogs pointed to new design considerations, in effect increased the designer's variety, allowing new ideas to emerge. We also used this design exercise to highlight four circularly interconnected activities, aligned with co-evolutionary design [DEG+14]. The first was a dialogs to agree on the goal, that is, to design a humanly space object. The second was a dialog to agree on the means, which included sketching, computer modeling and prototyping until a final design emerged. The third was a dialog on designing the design process, which included cybernetic circularity for the perspective, and design dialogs for the iteration cycles. The forth dialog involved the creation of a novel visual language that translated into the final object with simple and clean forms and aesthetics.

For artists and designers, a significant part of the creative process involves a circular dialog with the artifacts they create. While the process of sketching, and 3D computer modeling is suitable to experiment with initial ideas, building physical prototypes are necessary to gain deeper new insights. These range from slowing down the process and allowing for reflections, through refining feasibility by trial and error, to learning from constraints, barriers, and mishaps. Through this circular process, having a physical object (and to a lesser extend the drawn graphics by having an external representation) separates the making/knowing part of cognition and the viewing/experiencing part of cognition. Drawing an analogy to Design Dialogs, the making part can be equated with language, where the cognitive thought is expressed externally. In a connected way, looking at the object is equivalent to the sensing and interpreting part of perception by cognition. Consequently, a design activity is a dialog between the designer's cognition and the metaphysical world through making and observing. The process is negotiated or iterated towards a constructivist middle ground, until the designer is satisfied with the object. In a cybernetic sense, at that point the designer/regulator and the environment has a negotiated and equalized variety, at that specific temporal and spatial occurrence. We believe that understanding and leveraging these design dialogs is an important part of the creative process.

Subsequently we broadened the discussion from a single object to an interactive space habitat, which will become a point of departure for future research directions, where we will be developing a space habitat concept, based on cybernetic interactions, dialogs between the astronauts and their environments.

We also provided a brief discussion on design considerations, procedures, and identified resources which may help artist and designers with navigating the complex requirements from a space agency, like NASA, leading towards the acceptance, approval, and eventual flight of these space artifact.

VI. ACKNOWLEDGMENTS

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