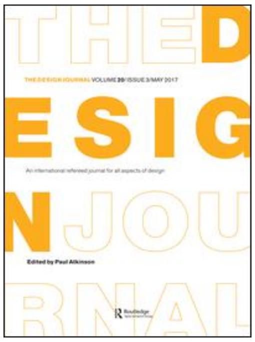

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Considering Haptic Feedback Systems for A Livable Space Suit

Torstein Hågård Bakke[a]*, Sue Fairburn[b]

[a]Department of Design, Norwegian University of Science and Technology
[b]Kwantlen Polytechnic University
*Corresponding author e-mail: torsteinhaagardbakke@gmail.com

Abstract: The paper explores protective equipment for work in extreme environments manifested in a proposal for a haptic feedback system for astronauts. It follows the thesis that the safety of astronauts wearing Extra-Vehicular Activity (EVA) suits, whether in space or on planetary surfaces, is connected to their ability to interact with their environments, their equipment and suits, and their coworkers. The project emphasises the use of new technologies to enhance the quality of said interactions. Focusing on manned exploration and construction activity in space, qualitative research methods are employed to gain an overview of the factors that dictate work in space, endeavours in design and architecture for space, and research into the ways humans interact with their surroundings. Lastly, a conceptual prototype was made to explore the possibilities of exploring a language of haptic feedback to complement other systems and to mediate the sensory filters imposed by the modern space suit.

Keywords: Haptic, Extreme Environments, Space, Personal Protective Equipment

1. Introduction

In the novel *The Martian* (2011) by Andy Weir, fictional astronaut, engineer and botanist Mark Whatney is castaway on the surface of Mars, assumed dead and left to his own devices by his crew. He survives by harnessing the powers of the man-made martian habitat, vehicles and space suits, cultivating food and undertaking extensive excursions on the surface of the red planet.

It seems as though some humans are bound to be martians. The first manned mission to Mars is imminent (Cuthbertson, 2018), and the space industry is rapidly expanding. Sending humans to live in space, however, poses challenges and opportunities that go well beyond the purely technical and logistic of getting there (Häuplik-Meusburger, 2014). The conditions of space are inherently hostile to humans, a challenge traditionally met with rigidity in engineering, incessant training, and extreme prudence (Hadfield, 2013). Human activity is characterized by physical and psychological hardships, and is extremely economic in its luxuries (Häuplik-Meusburger, 2014, Peldszus, 2018). But human activity in space can be expected to change and expand in a multitude of varieties, spanning the experiential spectrum from work to leisure and play (Kelly & Kanas, 1994). Thus, we plead that the gear we equip astronauts[1] with will be designed for a greater amount of versatility and disposition towards a multitude of activities, situations and dangers.

Living in outer space or on the surface of other planets will be a human experience situated in an extreme milieu, characterized by man-made environments, rigid protocols and limited social interaction (S. Barnett, John & Kring, Jason, 2003). This article highlights the space suit as a site of experience and interaction for human activity in space and as the primary piece of Personal Protective Equipment and attempts to countermeasure some of its hindrances.
Wearing a space suit, a pressurized tank with limited mobility and comfort, means confining oneself to an environment whose boundary is the only thing between an astronaut and the instantly lethal surrounding environment - a "microcosm that must contain all the things of Earth that humans need to live and work" (Thomas, McMann, & Thomas, 2012). Every aspect of interaction between astronaut and their surroundings is mediated through highly specialized materials and technologies, be it communication, tool use, or awareness of oncoming hazards. All sensory perception and interactions are translated and filtered through the suit.

1.1 Research Aim

The research departs from a short term investigation into the potential for innovation in the field of occupational health and safety in extreme environments and conditions. It attempts to combine a discussion on the technical, physiological, and psychosocial implications of human space exploration, working and living with a designerly, phenomenological stance on the experience of wearing a spacesuit.

While the research is manifested in a concept-stage prototype for a haptic feedback system for astronauts, it should also open a discussion on the meeting of science, engineering, psychology and design in an evolving and expanding space industry to aid human activity within extreme environments. Supposing that the mediation of interaction through the space suit directly affects the comfort, safety and efficacy of the wearer, the research is conducted to explore whether improving the channels these interactions are mediated through may be integral to implementing and maximizing human extraplanetary activity. It attempts to contribute to the countermeasure of factors that impede safe, successful, and enjoyable work and living in space.

1.2 Article outline

This article outlines the efforts of a graduate student research project on protective apparel conducted in the area of well-being and safety in human space endeavours. The research consists of semistructured interviews with key professionals in the industry and the review of selected academic and popular literature, media, psychological theory and existing design projects. It is manifested in a concept-stage prototype for a haptic feedback system designed to be implemented within the helmet of the planetary astronaut.

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[1] While conventions indicate that Astronauts, Cosmonauts and Taikonauts are all used to describe human space explorers, the author's use of Astronauts is intended to encompass all space explorers.

First, it will provide an overview of the background for the research through its departure as an investigation into the potential for innovation in personal protective gear in extreme work and living conditions, i.e. space. This precedes a justification of the phenomenological stance on situational awareness employed in the project derived from the field of embodied cognitive psychology. Secondly, the methodological nature of the work conducted will be described with regards to interviews, literature, art and media reviewed as aesthetic, technical and theoretical precedents, existing projects and prototyping. Following this, key insights from the research conducted are summarized, to provide a brief synthesis of technical and psychosocial implications for a design intervention. Then, the concept-stage prototype developed in the project, the Periphery Cap, is described in terms of intention, implementation and functionality. Concluding the reports on the work carried out, we discuss the efficacy and potential of haptic feedback systems and their continued development and the consideration of an embodied approach to space design.

2. Background

2.1 Environment Space

To sustain human life outside the Earth's atmosphere, Earth conditions need to be replicated, and for this there are extensive controls in place on spaceships, space transports, and in personal space suits. These systems exemplify telemetry and technology as the interface between human environment. Spacesuits represent a tight-fitting biosphere, a microclimate around a human body exposed to the very extreme environment of space (temperature and pressure extremes). Different suits are designed to address different environmental contexts: Extra-Vehicular Activity (EVA), Intra-Vehicular Activity (IVA), Surface, and Zero-g. The Extra Mobility Unit (EMU) space suit used for spacewalks, allows the astronaut to manually control their internal environment and to sustain their basic physiological needs through the PLSS (Personal Life Support System).

The risks of space exploration are varied and one of the primary sources are extravehicular (EV) hazards (Kosmo, 1987). Figure 1 shows data on 'significant incidents and close calls' - such incidents arise from unexpected meteoroid and space debris particles but significant incidents also arise from human-activity such as 'inadvertent releases' involving man-made items that should be restrained but become unintentionally freed (e.g. tools, fasteners, equipment, etc.) (NASA, 2018)
EVA's are monitored remotely, in real time, so support ground personnel can look for anomalies to detect changes, anticipate incidents, and support remote decision making. However the remote nature of monitoring, even in 'near real time' is of little benefit when communication delays add life-saving seconds and minutes to the astronaut's awareness of oncoming hazards. Hence the opportunity afforded to explore and conceptualise designs to augment the sensory perception and situational awareness of spacesuited humans carrying out activities outwith the protection afforded by planetary structures and vehicles.

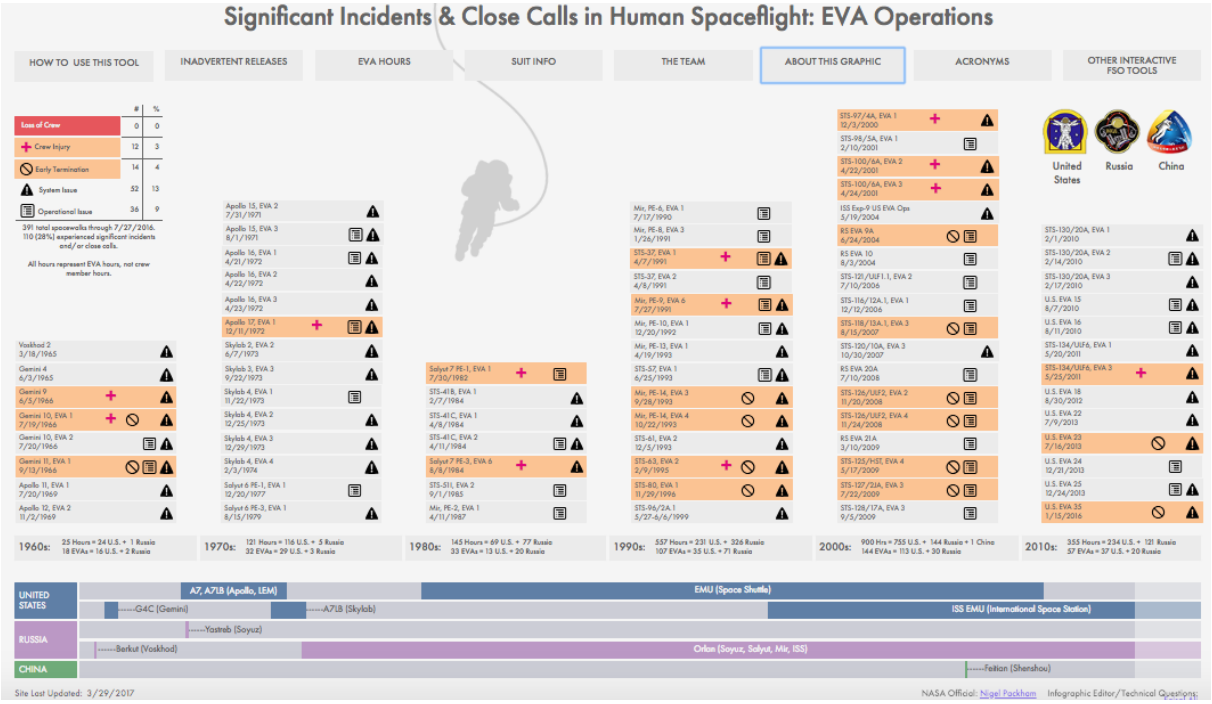

Image 1. Infographic (Courtesy of JSC SMA Flight Safety Office, 2018).

2.2 Design for Space

As a discipline, design embraces the world of imagination, culture and technology. When considering the genres of space architecture Imhof and colleagues proposed three genres - the first designs are those inspired by science fiction books and films and referred to as '*Voyage d'Espirit'* (Imhof et al, 2005 p.215). Genre two is named '*Man-in-a-Can*' because of the archetypical shape of the cylindrical rockets and cargo bays seen in the spaceships designed by Engineers, Architects and the various governmental space agencies in the first 50 years of spacefaring. Genre three highlights the ideas and imaginations of independent Architects and Designers who ground their ideas in the familiar terrestrial environment but expand them to access extra-terrestrial environments - and this genre - '*Trans-Gravity*' draws inspiration from the earth-space continuum and expands on the practice of design in space integrating the relevant human factors and qualities of life. Of interest is the notion of 'Machine-type' as a 'man-made device with interrelated parts that work together to perform a task' (Imhof et al, 2015), and it is this definition that offers a starting point to challenge the device, in this case, the spacesuit, and aim for 'human-ware' instead of 'hardware'.

2.3 Human Physiology in Space

Human physiology and morphology is subject to intense challenges that are brought about in space due to microgravity and other factors (Dominoni, 2008).
Body fluid is no longer directed by gravity to the legs, but evenly distributed, meaning more fluid to the head than usual, leading to the characteristic "puffy face" and "chicken legs" (Gunga, 2015). Lack of gravity also contributes to the diminishing of muscle and bone mass, which affect responses and bodily coordination in microgravity. The senses are also affected with diminished taste, reduced perception of color, and indigestion. Since gravity can no longer assist swallowing, astronauts must learn to do this "manually" (Gunga, 2015).

Environmentally, temperature changes may be abrupt, with the connotations this has in terms of human physiology both at rest and when actively working. Radiation up to 1000 times what you would normally experience on Earth is present and therefore all structures (habitats, transport and spacesuits) are outfitted with sensors monitoring exposure and feature numerous layers of protection.

Mobility is usually an issue the first few days in space, before the astronauts are accustomed to the microgravity environment, when they are able to do acrobatics and move freely about (Hadfield, 2013). With the absence of gravity, the body naturally assumes the Neutral Body Posture, which is different from any resting posture on earth, having implications for clothing design, specifically spacesuit design and working postures. All fluids, including for example tears and sweat, form spheres, which may float around the environment (Dominoni, 2008). While this seems harmless, space suit water intrusion and circulation during EVA's can be life-threatening when it affects the astronauts vision and breathing, as in NASA Case number S–2013–199–00005 involving a mishap on July 26, 2013 (NASA 2013). Dead skin cells and other biopollutants also float freely in the interior (Dominoni, 2008). Hazards within the suit are further complicated by hazards outwith the suit, as previously outlined. Should the space suit be compromised in the vacuum of space, or the astronaut be hurled out of a spacecraft or station, the body will expand as it decompresses, radiation will penetrate cell walls, and the oxygen will deplete from the cells, causing death within 90 seconds (Landis, 2009).

2.4 Architecture, Livability and Awareness

Häuplik-Meusburger (2011) makes perhaps the most extensive analysis of space habitat architecture, successfully reviewing a number of habitats from the angle of physical and psychological well-being and human activity. Through interviews with astronauts, she assesses each habitat according to a number of factors, highlighting the notion of livability. We may understand livability through a phenomenological lens as the human experience of living in space. Häuplik-Meusburger's interviews unveil experiences of high cognitive loads, extraordinary conditions and the combination of extreme fascination, engagement, stress and fatigue.

The relationship between designers and space agencies has not been prioritized for many missions. In the late 60's and early 70's, however, prolific designer Raymond Loewy was commissioned by NASA to design spaceship interiors to promote the well-being of astronauts and, down the line, non-astronauts and space-tourists. He also served as consultant for the International Space Station (Novak, 2014). In the late 20th century, the work of Constance Adams and colleagues at NASA's Habitability Centre pushed the human aspects of living and working in space and left a legacy that inspires the current and emergent generation of designers (Adams and McCurdy, 1999, Kenedy and Adams, 2000).

It is likely that despite the exhaustive preparation and training astronauts undergo (Hadfield, 2013), and our knowledge of the many stresses they experience in space (Häuplik-Meusburger, 2011), they may still not prepared for the multitude of scenarios and situations in which they may find themselves. The most important element may be determining when to be alarmed, or as Hadfield writes "if you're not sure what to be alarmed about, everything is alarming." (ibid, p52).

2.5 Phenomenological Approach To Design for Space

This article relies on illuminating the phenomenology of human activity in space, and the results of the efforts focus on the lived bodily experience. To ground this in cognitive theory, we turn to Merleau-Ponty's notion of embodied cognition as partly defined by a bodily disposition towards tasks, coming about through experience in an "intentional arc" which "projects around us our past, our future, our human milieu, our physical situation, our ideological situation, and our moral situation, or rather, that ensures that we are situated within all of these relationships." (Merleau-Ponty, 1945)

> "The body's relationship with space is therefore intentional, although as an "I can" rather than an "I think"; bodily space is a multi-layered manner of relating to things, so that the body is not 'in' space but lives or inhabits it." (Toadvine, 2018)

Astronaut knowledge of a situation is usually due to training and rehearsing, resulting in occurrent beliefs that often are relied on to emerge from biological memory. Can we imbue things and systems in the environment with cognitive properties, things that don't fall victim to failures that humans are prone to under the demonstrated stress of space activity (Häuplik-Meusburger, 2011, Hadfield, 2013)? Considering the offloading of mental activity, for example to a notebook for regular humans, is arguably no less reliable than access to biological memory (Clark, 1998).

Clark (2008) also considers the notion of bandwidth - an internalized memory connection to information that may be seen as having more bandwidth than the reading of, say, notes in a notebook. For a designer, one might consider the ways in which we may increase this bandwidth, or appropriate the form of information to the relative bandwidth of the channel, in this case haptic feedback as a way to offload the visual sense. This is also inspired by the critique of visual focus (as opposed to other senses) in architecture and design by Pallasmaa (1996).

Anchored in this theory, we may define the astronaut and her suit, her tools and the surrounding environment, as a unified cognitive system, in fact it might be reckless not to do so. If we cede that the spaceman in her suit is one cognitive system, framing cognitive systems in the personal protective equipment domain (and there is reason to do so as a design heuristic) allows us also to analyze them in the terms of safety systems and the demonstrated psychological effects of prolonged space travel (Oberg, 2007).

2.6 Haptic Systems

Several entities are exploring the use of haptic systems in developing new interactional technologies in safety, consumer products, surgical medicine, and arts (Giordano et al., 2015, Cranz, n.d., Lindeman, Sibert, Enyati et al, 2016, Lathan, & Vice, 2004) as a response to issues of cognitive load or deficiencies. Novich & Eagleman, 2015, demonstrate how touch receptors in the skin can relay abundant forms of abstract information, including but not limited to words, directions or stock-market data. Their findings indicate where (on the body, with sufficient spacing between vibrotactile motors) and how (encoded in space, time and intensity) information is best relayed. Other work (Eagleman, 2018) details the translation of language inputs into haptic output on the body, as demonstrated in the Neosensory Buzz, a wearable for the hearing impaired that translates language into vibrotactile information (Neosensory, 2018).

A framework is proposed for the hierarchical structure of functionality in the domain of space safety systems (Figure 2) informed by frameworks within Occupational Health and Safety Hierarchy of Controls (NIOSH, 2015). The innermost layer of this structure denotes **protection** - all measures, mechanical and technological, taken to shield the astronaut from hostile factors of the surrounding environment such as the lack of air or radiation without which the astronaut would perish. In a broader sense, the protective layer should also ensure the prolonged survival and physical and psychological well-being of the astronaut.

The next layer concerns **perception**. This entails the systems through which the suit perceives the environment surrounding it. It comprises the systems that monitor, measure, and the nature, diversity, denomination and quantity of data relevant to life support systems.
On top of this is the layer of **awareness**, which denotes the systems that at once process the data perceived and relays it to the astronaut. It might be seen as the mediation of information from outside and within the system to the user. It will be argued that this constitutes the availability of beliefs in a unified cognitive system comprising at once the astronaut, the suit and the environment surrounding it.

The uppermost layer is that of **interaction**. It is the parts of the system that allow the astronaut to enact his intentions upon the environment, such as the mobility of the suit or control of robotic fixtures. It allows the astronaut to be part of the world through the embodiment of her cognition as manifested in the behaviour of the system.

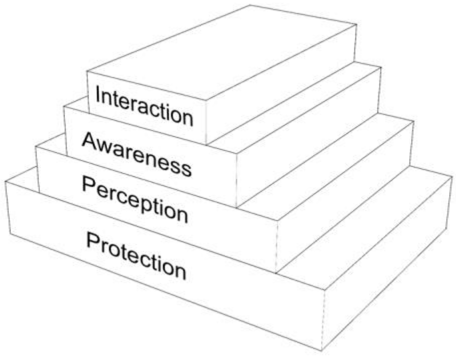

Figure 2: A proposed Hierarchy of Function in Space Safety Systems

3. Methodology

The research conducted in this short term project (six week timeline) was primarily qualitative and exploratory, seeking to complement the technical knowledge and logistics of space travel with the phenomenology of experiencing space. A literature and media review was carried out, primarily and purposefully within the realm of first-hand accounts, interviews, case studies and popular fiction, consistent with the ‘trans-gravity’ genre of design for space (Section 2.2). This approach was appropriate for the research aim in that it provided experiential data on human activity in space and designing for extreme environments. The first-hand account of astronaut Chris Hadfield (2013), interviews of astronauts by space design researchers Sandra Häuplik-Meusburger and Regina Peldszus, and first hand accounts of designing architecture and equipment have contributed to the construction of a phenomenological contextual framework. The interviews may be categorized as primary research (to inform the project and prototype) and reflective (to evaluate the concept and execution).

Science fiction, books and movies provide a lens through which we might speculate in a highly visual sense about the future of space travel and the technology we might develop. It also provides a view from the stance of creative professionals, as perpetuated in the audience (Peldszus, 2018). It provides insight into the influence of real-life endeavours on science fiction, as well as the other way around, as exemplified by the production of the seminal 1968 Stanley Kubrick film *2001: A Space Odyssey*, whose aesthetics in turn influenced later missions (Ljujić, Krämer, & Daniels, 2015). Other projects in the realms of art (Morby, 2017), space architecture and design (Paterson, 2014, Novak, 2014, Doule, Šálený, Hérin, & Rousek, 2012, Shee Consortium, 2015), protective gear and clothes for extreme environments (Fortunati, Katz, & Riccini, 2003, Mears, 2017) and embodied and extended cognition systems (Dourish, 2004, Lakoff & Johnson, 2008) helped established an aesthetic, technological and academic background for the project, illuminating the interest in and precedents for a design project for space that incorporates notions of protection, awareness, embedded cognition, human factors and habitability in space.

The project aims to manifest the human-centered, embodied and phenomenologically grounded approach in a prototype preempting a design intervention in the realm of awareness and interaction. The conceptual prototype is understood as methodology in its own right, allowing for the testing of certain attributes before a finalization of the design (Cypriano & Pinheiro, 2015). In this case it constitutes a first approach to the integration of haptic feedback within the helmet of a spacesuit. Thus, initial impressions could be gathered on the workings of the system. This includes donning/doffing the prototype, experiencing the sensations of the haptics, experimenting with their correlation with the orientation of the hand, translating and deciphering meaning through the feedback, and the effects of prolonged wearing of the prototype.

4. Findings

The following are key takeaways and findings of the literature review and the interviews conducted. Findings are highlighted as those relevant to the research project, the development of the prototype, or the illumination of the experience of space living.

Book: Chris Hadfield, Retired Astronaut. In his book “An Astronaut’s Guide to Life on Earth” (Hadfield, 2013), illuminates the road to becoming an astronaut, as well as getting to and living aboard the International Space Station. The book served as an apt introduction to the area as the research project was initiated. In an effort to translate the essence of the astronaut work ethic into “real world” advice in achieving seemingly insurmountable goals, his recounts of the intense training regime and endless simulations of operating procedures in jet piloting, spacecraft maneuvering and maintenance/expansion of the space station and its connected equipment brings to life an image of the fragility of life in space.

The social life of astronauts, he writes, is strained by lack of privacy, compact living quarters, exposure to just a handful of people over several months, and the relentless scheduling and monitoring by the ground control crew (an aspect of space life that for one mission culminated in the 24-hour mutiny of the crew of one spacecraft).

Hadfield includes a series of anecdotes illustrating the fragility of the completely man-made environment, exemplified by one in which residue from visor cleaning liquid blinds him during an extravehicular mission. The book provides the project with experiential accounts of life in space, as well as inspiration for design intervention concepts in terms of the spacesuit and the challenges encountered within it as protective equipment. Accounts such as these may reveal shortcomings in any one of the four realms in the proposed hierarchy of function (fig. 2).

Interview: Bill Dieter Designer and founder, Terrazign, USA, relays his experiences with design for space (Dieter, 2018) during the research phase of the project. For NASA, they designed and manufactured the Glenn Harness for the ECLS “space treadmill” for personal exercise to mitigate loss of bone density and muscle mass (Giannone, 2011).

Gravity, he says, affects absolutely everything in space, and “once things go up, everything changes”. However, he mentions that there are certain advantages - efficient 3D-printing may be done in microgravity, and the moving of heavy material and equipment.
His perspective is that in a practical sense, “humans shouldn’t be going into space”, and that the health of the first people to get to Mars is imperative - there will be no doctors, just robots. Therefore, keeping fit is imperative to the astronaut even though the gravity on Mars is one-third of that on Earth. The volume of a Mars shuttle may be very limited, and everything that is designed for space is designed with this in mind.

Big challenges for a suit on the planet will be temperature swings, radiation, and oxygen supply. They are currently working on building suits that simulate the environment on Mars to prepare astronauts, underlining the question “What will it feel like to land on Mars after several months of weightlessness?”. They are focused on simulating the fatigue that getting to Mars will entail, physically and mentally, as there will be a lot of stuff to get to once they are there.

Terrazign has been looking into using sensors in textiles to monitor heart rate, metabolism etc. They have also looked at Augmented Reality, which may be very relevant to my research project - info overlay, haptic feedback, auditory feedback. Haptic feedback, he says, is not hard (with, say, vibromotors), but implementing it right might be. It might aid the dexterity of gloves, or give subconscious clues to the surrounding conditions (such as wind) (Dieter, 2018).
Dieter’s insights illuminated areas of both technical and user-centric importance in the design of space equipment.

Interview: Sandra Häuplik-Meusburger, PhD, Assistant Professor at TU Vienna, (Häuplik-Meusburger, 2018), was interviewed shortly after the prototype was developed. She highlights non-visual and non-auditory perception as an underdeveloped feature in architecture for space. The scale of space architecture is consistently small - habitable space is very confined. This leads to issues of privacy and personal space, as habitats are often experienced as crowded. This is not just in relation to the actual size, but also the socio-cultural makeup of the crew (Kuznetsova, Gushin, Vinokhodova, & Stepanova, 2018). Architecture for space, and subsequently ”personal architecture” like a suit, must also consider mitigation of claustrophobia, fear and anxiety to ensure livability and comfort.

All EVA will be done by, or at the very least with robots. However, there are skills that humans are still better at, such as critical thinking or incorporating spirit. This is exemplified by the Apollo 17 mission, where humans knew to bring back valuable stone samples from the moon that a robot would not have known to prioritize.

Häuplik-Meusburger's comments relate to and complement her work which has been extensively referenced in this project. Her work provides ample foundation for speculation in the field of design of equipment that relate to the human body, psychology and experience in space.

Interview: Regina Peldszus, PhD, DLR Space Administration, Germany interviewed after the construction of the prototype, responds to the proposition of a head-mounted haptic feedback system saying it is both timely and topical, constituting, in the nomenclature of the industry, a countermeasure to a stress (Peldszus, 2018). Stressing the importance of utilizing the RAMS framework, she recommends an inquiry into the psychology of situational awareness. She also turns the attention towards the work done by Dava Newman on developing a kinetically, as opposed to pneumatically, pressurized suit that will increase mobility and agility for the astronaut while reducing bulk (Flaherty, 2014). Discussing with Peldszus after the realization of the prototype helped evaluate its efficacy and potential, as well as positioning the concept on the spectrum of endeavours in space PPE. Her comments on designing for, and disseminating design to, a space community contribute to advancing the concept into feasibility, mitigating the speculative with the real and facilitating fruitful cooperation between fields.

NASA: Standards: Designing equipment for space also must adhere to technical standards as outlined by the NASA Technical Standards, such as NASA Spaceflight Human-System Standard Volume 1, Revision A: Crew Health (NASA-STD-3001 VOL 1, 2014) which outlines the standards for addressing the health of crew members during all phases of space flight.
As of 2010, NASA standards that apply to design and architecture are compiled in the Human Integration Design Handbook (NASA, 2014), complemented by the Human Integration Design Processes document (NASA, 2014), which outlines the NASA procedures and methodologies for designing for space. The design methodology is heavily reliant on Human Centered Design activities, which served as a central approach informing the prototype of protective equipment for the extreme environment and conditions of space that follows.

5. Concept-stage Prototype: Periphery Cap Insights

5.1 Intention

The intention of the conceptual prototype is to explore the somatosensory properties of haptic communication on the skull, and to assess the potential of using the communicational domain of haptics and their bandwidth to mediate certain kinds of information through the filter constituted by the EVA space suit. Lastly, it introduces a provisional processing of input (finger bending and hand orientation) to output (vibration of varying intensity on different point along the circumference of the cranium), as a starting point to open a discussion on how to, in the most appropriate way, incorporate cranial haptic feedback in a space suit seen as a unified cognitive system.

5.2 Functionality and Structure

The *Periphery Cap* is intended to be worn within the helmet, and is fitted with an elastic band to provide a snug fit for the wearer. Aesthetically, it references the Communications Carrier Assembly used in NASA spacesuits, which houses earphones, microphone and radio (MSFC, 2013). The *Periphery Cap* is constructed of synthetic textiles, with a fleecy inner lining for comfort. A nylon strap with plastic buckles secures the cap to the wearer (Figure 3).

Six vibration motors are positioned along the circumference of the cranium. One motor is situated at the front of the forehead, two others at the temples in front of the ears, two others still behind the ear, and the last one in the small of the neck. The motors are sewn into the fabric and are not visible save for the wire coming of the back of the cap. The vibration motors are spaced with low density as the Pacinian corpuscles, mechanoreceptors responsible for sensing vibrations in the skin, have a relatively large size of receptive field (Freberg, 2018).
For this iteration of the prototype, the motors are connected by wires to a circuit board sewn on top of a glove. The circuit board houses an Arduino Nano microcontroller, to which the vibration motors are connected.

The circuit board also features an accelerometer (ADXL335), also connected to the Arduino. The gloves is also fitted with flex sensors (SEN-10264) on the thumb, index and middle fingers, that in turn are connected to the Arduino (see Figure 4).

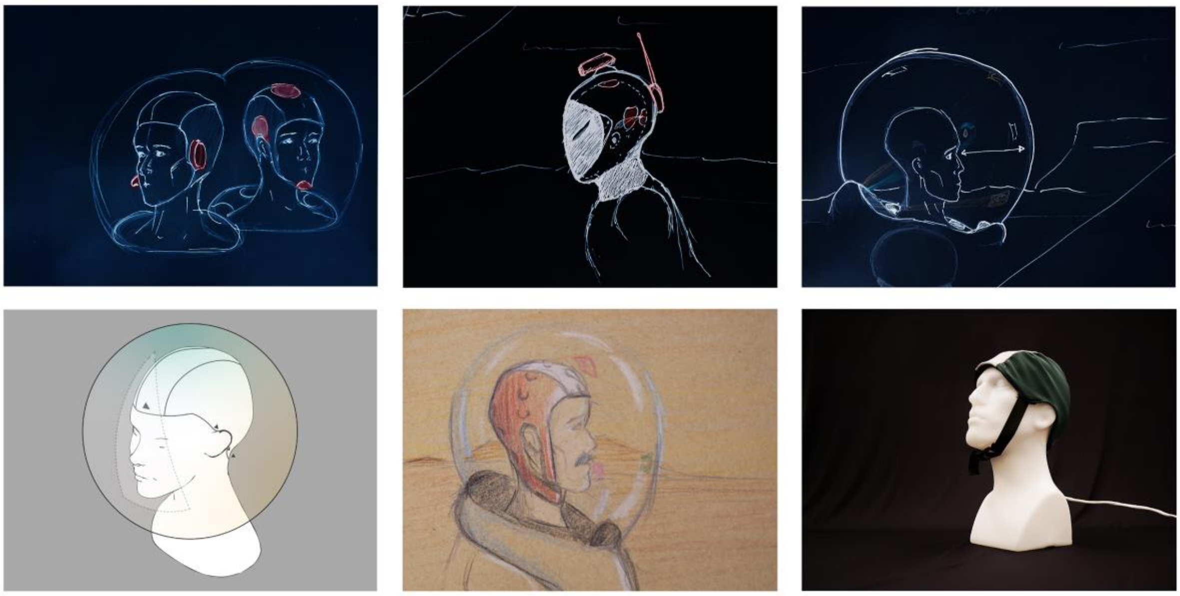

Figure 3: The Periphery Cap Conceptual Sketches and Prototype (Image credit: T.H. Bakke)

The Arduino is programmed so that movements of the hand wearing the glove correspond to variations in intensity in the vibration motors within the cap. Haptic sensations are subject to rapid rates of adaptation, meaning the mechanoreceptors responds as stimulation starts, ends or changes drastically, but remain unresponsive as stimulus is applied continuously (Freberg, 2018). Thus, it’s implied that a haptic feedback system must be encoded with a temporal structure (Novich & Eagleman, 2015)

Bending each of the three fingers fitted with flex sensors produce vibration behind the ears and on the forehead, while changing the orientation of the hand such as rotating it or bringing the palm up (as measured by the accelerometer) produces vibration in the temples and the small of the neck. The degree of bending or orientational deviation is reflected in the intensity of the vibration. Keeping the hand level, steady and with the fingers stretched out produces no vibration - from this departure point the user may use her hand to explore movement-sensation relations.

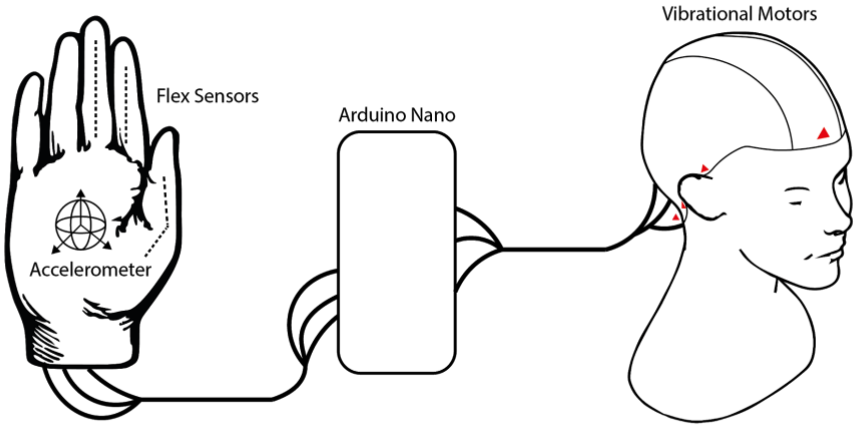

Figure 4: Periphery Cap System Diagram (Image credit: T.H. Bakke)

5.3 Insights

Preliminary testing by the authors shows that the prototype is capable of delivering haptic sensations to the scalp of the wearer. Every motor is perceivable and discernable from the others, albeit some are harder to feel than others, particularly the one in the small of the neck. This may be attributed to the fit of the cap. The glove is working satisfactory - however, after a while the mere exploration of which inputs result in which vibrations becomes uninteresting. Wearing the cap for a longer period seems to habituate the wearer to the sensation, up until the moment where the hand is moved violently or unexpectedly, at which point the stimuli becomes very prominent.

Further study of the prototype as it is imbued with more functionality could unearth an emergent “language” of haptic feedback. Other projects using haptics (Novich & Eagleman, 2015) show that people can learn and adapt to signals and patterns that are both dynamic, contextual and highly complex. Testing implies a high grade of sensitivity and discrimination towards variations in intensity in the wearer, which can be utilized to program for a spectrum of alerts. This higher level and resolution of control in terms of alarm may aid in making better health and safety decisions. Feedback from contributors and experts suggests that the concepts and the further studies that are implied are in tune with current endeavours, while being considerate of a holistic view of human factors as they have been proven to be integral to the objective and perceived success of space missions.

There is ample space for developing the prototype further. Primarily, the cap should be reconfigured to react to stimuli that is not the result of the movement of the wearer. Preferably, the next iteration would give off patterns of vibrations that relate to the position or movement of the constituents of the environment relative to the wearer, for example giving off vibration in the small of the neck if an object enters the field directly behind the wearer. Implementation of proximity sensors or depthsensing cameras may aid in this endeavour. In the eyes of the author, considering feedback from the expert advisors and from preliminary, provisionary testing, the concept shows promise as a cognitive aid in the realm of situational awareness.

6. Discussion

A haptic feedback system is proposed in this article as a way to mitigate the filtration of sensory input through the layers of the space suit. We know that it is possible to encode information through haptic feedback - we are all familiar with it through our cell phones. The intimacy of the technology (needing to be physically in contact with the actuator) also reduces it's invasion into the cognitive spheres of others. We've seen examples of haptics compensating for loss or deficiency of other senses, and even constituting new senses altogether (i.e. a "stock-market" sense, (Novich & Eagleman, 2015)). This research also proposes haptic feedback as a means to relieve the user of a cognitive load, by shifting information or alerts to the appropriate channel. Following the critique of Pallasmaa (1996) on the over-reliance of the visual sense, a haptic cap may allow the system to relay information that is more naturally relayed through touch rather than vision, to be relayed thusly. More research is needed on the kinds of information that is more aptly relayed thusly, and how.
The question of how to translate information into haptic sensation warrants more research, even as work is being done and concepts presented (Lindeman, Page, Yanagida, & Sibert, 2004). A possible route for the further development of this project might be the development of a "haptic language", using a grammar of vibration to translate vibrations. This could be conceived as a one-to-one translatory tool, corresponding to certain events in the spacesuit perceptive system or even words. However, reflecting on the varied, contextual and dynamic way in which people process perceptions and meanings, we might also speculate in the use of intelligent systems that dynamically appropriate the mode of mediation to the situation. In particular, such a system could challenge how users are alerted to and dealing with hazards while using PPE. This approach would warrant extensive research on human processing of haptic signals, perception of contextual factors, and dynamic, intelligent relational systems.

This leads us back to the notion of embodiment in designing for interactive systems in the context of extra-terrestrial occupational health and safety. Such a system would in essence require a computer system capable of making phenomenological inquiries as to the state of the user and her surroundings. This human-centered approach to design has at its core a mandate to alleviate and offer countermeasures to environmental, psychological, physiological and social stressors. On the other hand, it opens a discussion on how technology, through this approach, may enhance the experience of exploring, working, living and playing in space, elevating a protective system such as the space suit to a successful interactional level. An embodied, phenomenological approach to design, it is argued, has a place in the space exploration endeavor as it attempts to ameliorate and mitigate the physical and psychological dangers of being in space. This could also prove to be a fruitful meeting point for designers and engineers, as well as the dissemination of experiential knowledge of extraterrestrial living.

7. Conclusion

A phenomenological approach to designing for space, an inhospitable realm in which all experience is mitigated through man-made systems, may prove beneficial both to the efficiency of research and work, the well-being and safety of astronauts, and could also contribute to enhancing the experience of being human in space and make it more enjoyable.

It is proposed that a haptic feedback system like the Periphery Cap could aid in this endeavour. The presence of research in the field of design relating to space exploration and colonization and it's appropriate dissemination towards the space research community can enrich the field and push the endeavour in a fruitful direction.

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About the Authors:

Torstein H. Bakke is currently writing his Master's Thesis in Industrial Design, which focuses on embodied interactional systems and experience design.

Sue Fairburn is Design Faculty and a Researcher with interests in positioning design between the body and extreme environments.

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