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Close encounters of the HCI kind: An ethnography of human-centered approaches in space technology

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Matthew Garvin

ABSTRACT

As NASA prepares to embark on long-duration crewed space exploration, solving issues related to the design of information systems and digital interfaces become increasingly important. Such systems have to enable informed decision-making for crews, who for the first time in the history of human space exploration, will begin conducting missions autonomously from Mission Control. This change must effectively replace dozens of flight controllers and other subject matter experts who up to this point, have been able to provide problem-solving capabilities through real-time communication. This thesis presents an ethnographic exploration of astronaut autonomy by unpacking the human-centered approaches observed through sixteen months of fieldwork on teams inside and outside of NASA. Observational, interview, and archival data were synthesized and analyzed to focus on two questions: How do space systems engineers conceptualize user needs when designing useful systems to support astronaut autonomy? What is the emerging role of HCI in supporting deep space exploration? Our findings suggest that engineers display a tendency to prefer a technology-centered engineering rather than a human-centered design approach. These findings also indicate that the systems engineering skill set may an advantage in human-centered design activities when such activities are invested in upfront and incorporate user needs into requirements. Additional insights describe how system requirements are typically prioritized over user needs, and how the absence of a human-centered culture causes problems later in the development process.

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INTRODUCTION

NASA is going back to the Moon, and then to Mars. If current plans proceed as scheduled, the Artemis mission will put American boots back on the lunar surface fifty-two year after the last Apollo mission in 1972, only this time we plan to stay [1]. In that time, emphasis in computing technology has shifted from hardware to software, from software to user-centered, and from user-centered to socio-technical systems [2]. Supporting astronaut autonomy with optimal interface design and “smart” technology is coming to the forefront. Here we define autonomy as the degree to which an individual or team is free to make decisions and solve problems at their discretion [3], [4]. To achieve these goals, technology not only has to be easy to use, but has to support the ability for crews to operate autonomously from the dozens of flight controllers and subject matter experts they currently have access to for real-time troubleshooting, just-in-time training, system maintenance, and procedure execution [5], [6]. This increased need to design for crew autonomy presents critical crew health and safety risks that require further investment into interface design to minimize such risks and ensure good usability and user experience.

For these technologies to effectively bridge the gap left by the absence of real-time communication with Mission Control, information systems and digital interfaces have to be designed with a focus on supporting the human user. Crew interfaces have to enable the ability to adapt to the unforeseen rather than be developed with a brute-force autonomy common in commercial “smart” technologies. What we find in practice is that while current autonomous computer systems like autopilot are seen as reliable, Harris describes automation as promoting boredom and disengagement when not properly designed with the human user in mind [7]. Complicating matters, such systems are designed to hand control back to the human at the first sign of trouble, whether the human is ready or not, increasing the likelihood of what tends to be classified as human error [8]. Often this human error is attributed to the end-user rather than the numerous designers, engineers, or other stakeholders who have a hand in the build along the way, and often the recommendation is to burden the user with additional training.

Furthermore, Holden reports that many issues related to human-computer interaction are only informally discussed and not followed up on because of a high level of confidence embedded in the culture of the crew [5]. This may cause crew members to be more accepting of usability issues if they think they can figure it out. This results in the situation we see on the International Space Station, where due to poor usability, many of the information displays are controlled by the ground rather than the crew itself, a clear indication of an inadequate design process [5].

To develop insights concerning these challenges, we conducted design ethnography as a UX designer on two project teams contributing to NASA competitions, followed by an internship as a UI Architect within an element of the NASA Human Research Program. In this thesis, we report on findings from an ethnography that involved a series of twelve semi-structured interviews and over 100 contact hours of participant observation.

The research questions include:

- How do space engineers conceptualize user needs when designing information systems to support astronaut autonomy?
- What is the emerging role of human-computer interaction in supporting astronaut autonomy?

Our findings suggest a technology-centered culture that prioritizes system requirements over user needs, and how this absence of a human-centered culture can cause problems later in the development process. Additional insights indicate that systems engineers may excel at engaging with human-centered design activities when such activities are invested in upfront and incorporate user needs into requirements.

This work contributes to centering the human in human-centered design projects by synthesizing human-computer interaction and human-systems integration. To improve the value of the ideas and experiential outcomes generated by NASA University Design Challenges and improve innovation within NASA's Human Research Program. The following Related Work section is organized to provide an overview of human-centered design within the field of human-computer interaction, outline prior work in human-centered space technology, and some of the more recent work within NASA's Human Research Program. The remaining sections detail the data collection and analysis, present findings, and discuss directions for future research.

RELATED WORK

Our research is framed around three areas of related work: HCI and human-centered design; Human-centered approaches in automation at NASA; NASA's Human Research Program.

HCI and human-centered design

Much prior work exists on human-centered design in the field of HCI. Indeed, it is even included as ISO 9241-210:2019, which emphasizes the human-centered design in interactive systems, defining user experience as the user's perception and response while using an artifact, and that, "achieving a good UX is the goal of the human-centered design approach," [9]. In a review of CHI publications, Harrison et al., discuss the emergence of a third paradigm in HCI [10]. The first being that of the human factors engineer seeking to reduce errors. The second being that of the behavioral scientist attempting to optimize the system through a reduction in ambiguity. This third wave, as characterized by the authors, is that of the ethnographer, who is more interested in what goes on around the system than what happens at the point of interface. Among the leaders of this third paradigm, Beyer and Holtzblatt defined contextual inquiry as a means of capturing qualitative insights to understand and specify the context of use [11]. Hashizume extended this work to present a human-centered application of contextual inquiry through ethnographic interviews [12]. Similarly, Baskerville and Myers argue for a new kind of design ethnography [13], derived from applied anthropology, which synthesizes participant observation with participatory design so that ethnographic insights can be used to generate design concepts for the point of study. In terms of teaching HCI to engineers, Galindo highlights the importance of fine-tuning the HCI curriculum for graduate-level engineering students when specific domains are considered (e.g., aeronautics and aerospace), serving as a reminder that not all mainstream HCI practice is compatible with regulatory authorities in terms of life-critical interactive systems [14].

Regarding human integration and the breaking down of the human-machine interface, Farooq and Grudin discuss advanced technologies for human-machine communication which lead to a codependent partnership, constructing meaning around each other's activities and drawing meaning from each other's presence [15]. We find Schirner et al. seeking to move beyond traditional interfaces toward electrophysiological signals [16]. Similarly, Lloyd et al. see a path to move away from human-computer interaction toward a self-adaptive system utilizing brain-computer interaction to optimize autonomous and cooperative interactions [17]. Concerning self-adaptive systems, Huang et al. offer preliminary research on such systems which can refine their behavior through "feeling" and interpreting user intention via neural input, effectively putting the human in the loop [18]. However, we also find research related to issues of trust in automation. Both Stanton and Lee urge for the design of human-computer interfaces with semi-autonomous systems that aim to keep the user informed and maintain situational awareness [19], [20]. Gil et al. present a conceptual framework for characterizing cooperation between the human and cyber-physical systems to improve human integration [21]. Our research seeks to better understand how HCI is being adopted by space engineering.

Human-centered space tech

Prior work on human-centered space technology was first highlighted as an approach to cockpit design to promote decision making through human-centered automation and supplant a technology-driven process [22]–[25]. Extending this work, Schutte describes a radically different approach in human-centered design through using the human body as a metaphor in the design of the aircraft [26]. Schutte argues that it would take more than wings to make humans physically fly, such as internal navigation and legs capable of taking off and landing. Furthermore, while we have overcome these limitations through brute force advances in technology thus far [26], Brute Force Autonomy (BFA), is identified as a limitation in our ability to develop autonomous systems intelligent enough to mitigate risk in supporting crew autonomy [27]. Evidence highlighting factors including gaps in the users' mental models of how the automated systems work as well as weak feedback from the system as being strong contributors to automation surprises [28], [29].

Human-centered computing (HCC) is emphasized in NASA's Intelligent Systems Program as a revolutionary approach to systems design intended to foment an epoch of space exploration in which systems of humans and machines are optimized, freeing the human to engage in the kind of cognitive activities we excel at [30]. Ames Research Center and Johnson Space Center found a human-centered computing strategy proved exceptionally beneficial for collaborating on intelligent systems for both manned and unmanned missions [31]. Whereas Zhang approaches human-centered computing by adapting the theory of distributed cognition in the design of an intelligent flight-surgeon console at NASA Johnson Space Center, presenting a framework for the human-centered design of such distributed information systems as electronic medical records (EMR) [32]. Since then, NASA has demonstrated an increased interest in standardizing a human-centered process and implementing it into the conceptualization and design of next-generation space technology to support crewed deep space exploration. Recently, Tibor Balint sought to improve innovation at NASA through human-centered design by way of second-order cybernetics through boundary objects to stimulate design conversation [33]. Although Balint's research and findings are very similar to this study, Balint focuses on design in general, such as curating delight through astronaut pillow design [34]. Despite NASA's enthusiasm for human-centered computing, little work has attempted to shed light on how these concepts are implemented in current space engineering projects.

Human Research Program

NASA's Human Research Program Roadmap is a living web document available to the public that captures the broad spectrum of research covered within the HRP. While much of this research is beyond the scope of this study, some of this work is directly related. For example, according to Holden, issues stemming from inadequate HCI present a risk to mission success that could lead to a wide range of consequences. While there is an increase in the amount of information to display, an astronaut's physical and cognitive capabilities to view and process such information remains limited [5]. Holden goes on to note that there is scant user data available in the context of operational spaceflight and that many issues related to HCI have likely been concealed under constant contact with Mission Control. A recent contextual inquiry into the role of the flight controller indicates that intelligent information systems and autonomy-focused design are among the key capabilities required for future missions in deep space [35]. Salazar offers human-centered design considerations for voice-controlled spacecraft systems [36], where he stresses the importance of design process planning being led by a Human Systems Integration (HSI) practitioner to ensure that HCD activities are incorporated into all phases, including scheduling sufficient resources for evaluations that lead to further design iterations and optimizations.

Some space engineering teams focus specifically on human factors and HCI. For example, the HCI Team at Ames, part of the Human-System Integration Division, is actively involved in improving NASA design practices and contributes to improving interaction design to support astronaut autonomy. Marquez presents a crew self-scheduling application called Playbook, which was conceptualized and iterated over three years and tested in four analog missions at NASA Extreme Environment Mission Operations (NEEMO) [37]. Findings indicated Playbook could support crew self-scheduling. This is an important contribution to this point of inquiry because of the cost of space exploration. Detailed schedules must be created and maintained to ensure productivity and return on investment. Complicating matters is that scheduling requires meticulous coordination and is currently performed by dozens of flight coordinators working to ensure a myriad of activities involving specific pieces of equipment do not overlap and/or have a sufficient buffer period between them. The Wearable Electronics and Applications Research (WEAR) Lab at JSC is a collaborative effort between human factors and engineers to increase crew autonomy to bridge the gap between the crew and spacecraft by enabling mutual monitoring capabilities [38]. Moses sought to provide wearables to monitor CO2, an important contribution in spaceflight as zero gravity, in addition to a lack of natural convection, limits air circulation. This presents a risk to crew health that is not being properly monitored through fixed sensors, whose readings may not adequately represent CO2 levels in locations near the crew. While such work served to inform and guide this study through advances in technology to support astronaut autonomy, our work explores assumptions and mental models that space engineers hold about the astronaut as a human user of technology, and how such assumptions, when left unchallenged, negatively impact the user experience.

The analysis of this related work suggests that many challenges remain concerning the development of autonomous systems and corresponding interfaces to effectively support astronaut autonomy on crewed deep space missions. The findings presented in this thesis aim to provide insights into human-centered approaches and how to accelerate their adoption.

RESEARCH METHOD

In this study, we sought to investigate how space engineers conceptualize the user experience and justify design decisions to support astronaut autonomy. To do this, we adapted the design ethnography research method [13]. This involved the application of both participant observation and participatory design over sixteen months of fieldwork divided among three different project teams, to understand similarities and differences in how different groups of engineers thought of employing a human-centered approach to interface design. This included eight semi-structured interviews with members of those teams and four semi-structured interviews with subject matter experts in NASA. These subject matter experts, or SME's include: an HSI researcher (SME-1); a space human factors researcher (SME-2); a model-based system's engineer (SME-3); an astronaut (SME-4). Much as the related work outlined, design ethnography was selected as the ideal approach for this research because the method itself has been adapted and used for decades in HCI to identify user needs, particularly concerning the context of work [39]. In the following subsections, we describe the fieldwork timeline and description of activities that took place. We then move on to an explanation of accessing and engaging the contexts of immersion for data collection. Finally, we describe the triangulation of multiple data sources through the application of grounded theory.

Design ethnography

Ethnographic fieldwork involves a set of data collection strategies founded upon an approach known as participant observation. Participant observation is a strategic method that, "puts you where the action is and lets you collect data," [40]. Typically, time must be spent upfront engaging the field site and building rapport with the "locals", essentially putting them at ease in your presence enough to open up about their experiences. While the time needed can vary depending on the researcher's level of experience with the culture being studied, it is this level of engagement that makes fieldwork so potent in uncovering implications and opportunities in human-computer interactions [39], [41], [42].

This study was conducted across three different contexts: NASA SUITS, NASA X-HAB, and a NASA internship embedded on a model-based systems engineering team using human-systems integration in the Human Research Program. Working with the project team on the NASA SUITS Challenge served as the first site of engagement and allowed the ethnographer to gain access to the project team working on NASA X-HAB. Experience with these teams facilitated access to a NASA internship where these experiences both inside and outside of NASA could be evaluated against each other and synthesized into theoretical findings grounded in data.

The NASA Spacesuit User Interface Technologies for Students (SUITS) is a design challenge to engage with students in the ideation and creation of spacesuit information displays utilizing augmented reality. The SUITS Challenge specifies the primary objective as the development of a user interface in a head-mounted display (HMD) to support astronauts with extravehicular activities (EVA) during a lunar mission.

The eXploration Systems and Habitation (X-HAB) Academic Innovation Challenge is but one of several platforms NASA uses to build strategic partnerships with universities. This challenge, to address gaps in the research and develop space technologies to improve human spaceflight capabilities, was introduced in 2011 as a means of investing in a future in which NASA sets its sights on building a sustainable presence on the Moon, and then Mars. Participant observation of this team served as the primary source of data collection. Interactions through meetings, discussions, collaborative sessions, and co-design occurred daily through team message boards.

NASA's Human Research Program (HRP) was re-established at Johnson Space Center in response to President George W. Bush's call for NASA to, "gain a new foothold on the Moon and to prepare for new journeys to the worlds beyond our own." It's purpose is to develop capabilities and technologies alongside the Astronaut Program, and pursue further risk reduction expanding from space medicine and the physiological and behavioral effects of long-duration spaceflight. The mission of the HRP is to facilitate space exploration beyond low Earth orbit (LEO) by developing solutions to mitigate the impact on human health and performance, define habitability standards, and deliver advanced support technologies.

Access and data collection

Initial access to the SUITS team was negotiated through the program manager (S-1). The leadership team subsequently agreed to support fieldwork involving participant observation. After this initial investigation, we recruited members for semi-structured interviews. Fieldwork with the SUITS team was conducted over twelve months and resulted in 62+ contact hours through subteam, administrative, and mass meetings. Access to the X-HAB team was negotiated through one of the project's co-leads. The fieldwork was readily supported by team members. Similar data were collected over four months, resulting in 30+ contact hours. Access to the NASA MBSE team was negotiated through a lead scientist in one of the elements as a University Space Research Association (USRA) intern. Fieldwork was supported by the lead scientist to conduct participant observation, followed by semi-structured interviews with NASA subject matter experts outside the team to get a broader internal view of human-centered design and human-systems integration in NASA. Fieldnotes were primarily captured through jottings while 'hanging around' in a virtual meeting or reading conversations in Slack or Teams. Additional observations were logged in a digital notebook, however, these observations are limited as a result of information export controls. Semi-structured interviews were related to general insights and perspective on HCI in space technology and were conducted outside of working hours (See Appendix A for fieldwork timeline breakdown).

In addition to fieldwork, data were collected through semi-structured interviews with past and present leadership on both the SUITS and X-HAB teams, as well as leading human systems integration engineers in the HRP, a NASA model-based systems engineer, and a current astronaut. It is important to note that all interview participants from the SUITS team were also prior members of the X-HAB team. Interviewees spoke about their experiences participating in technical projects for NASA. They also discussed their motivations for exploring human-centered design in space technology. Informed consent was given by all interview participants to be recorded via Zoom or Teams. These recordings were then transcribed and used for analysis; n = 12, avg = 50 min, sd = 5.52 min.

Table 1 Interviews and role of interviewees		
Group	**Role of interviewees**	**No. of interviews**
1: (S)	SUITS team members	4
2: (X)	X-Hab team members	4
3: (SME)	NASA astronaut autonomy subject matter experts	4

With conferences all virtual for the duration of this study, they became convenient and advantageous sites for data collection. Throughout this study, the author attended the Space Tech Expo, Michigan Space Grant Consortium (MGSC) Fall Conference, and SEDS SpaceVision in 2020, as well as NASA's Human Research Program (HRP) Investigator's Workshop (IWS) in February of 2021.

With this context, this study was oriented towards several questions related to better understanding design and problem-solving processes as relevant to how engineers conceive of the user experience. These questions influenced and guided systematic data collection as well as drafting interview protocols (See Appendix B for a general interview guide).

- What problems are NASA trying to solve with university challenges?
- What value do university teams bring to NASA through these challenges?
- How does background influence how engineers think of the user?
- How do plans develop and change throughout the project?
- How do systems engineers come to understand how to support astronauts in space?
- How do engineers figure out how to design a good user experience?
- Is there a certain process engineers follow when designing for humans?

Data Analysis

This study's ethnographic approach explored people's experiences with human-centered design of crew-facing interfaces and informational displays. During fieldwork within the Human Research Program, the emphasis shifted to observing systems engineering and taking part in the design of interfaces in support of foundational research being conducted by scientists and clinicians planning future missions. Throughout sixteen months of fieldwork, we analyzed both primary and secondary data. Primary data included field notes, interview transcripts, and chat logs. Secondary data included presentation slides, meeting notes, reports, and prototypes stored in team drive folders as archives from previous projects. First, we cleaned the interview transcripts and prepared them for Keyword in Context (KWIC) indexing. KWIC is a derivative of concordance, a relatively ancient technique commonly applied to sacred texts to produce an alphabetical list of all substantive words. KWIC was first proposed as an indexing system in 1856 by the librarian, Andrea Crestadoro [43]. KWIC indexing preserves the keyword in the context of the sentence in which it is used. In grounded theory, in vivo coding is the most common approach and involves developing codes based on research subjects' actual words. Creating a word list and applying the KWIC are conceptual extensions of in vivo [40]. To do this, we filtered transcripts to only include participant responses. These were then loaded into text analysis software as a corpus of texts. A word list was generated to condense lemma word forms into a single type. In morphology and lexicography, the lemma is the base word that is entered into the dictionary [44]. For example, engineer/engineering/engineers were counted as a single word. This word list included 2245 unique lemma types. A total of 10 keywords were identified based on their relevance to the research questions (see Appendix C for keywords).

A KWIC list was then generated for each keyword. These lists include every occurrence of the selected keyword within the context of the sentence in which it is used. The KWIC lists constituted open coding. Some examples of the concepts derived from this coding sequence include:

1. "It's called the [System]s [Engineer]ing Vee."
2. "We tried it out ourselves, but we didn't do any formal [test]ing."
3. "You have to convince everyone that your standard is better and [people] are reluctant to throw something out completely."

These initial codes then contributed to an axial coding process, where concepts were annotated within interview transcripts and fieldnotes to capture patterns among data identified in open coding. An example of axial codes includes, "engineers are receptive to human-centered design," "safety is the minimum viable product (MVP)," "human behavior is viewed as a black-box." Finally, we conducted a selective coding, to relate the various codes generated into a single narrative. These three stages of coding reflect the application of grounded theory, where coding is an iterative process. In between stages of coding, numerous memos were drafted, connecting pieces of data and developing hypotheses to test through theoretical sampling, a core component of grounded theory often missing from its application in the IS literature [45]. Given the generative focus of this study, and ethnography in general, data analysis is ultimately tied to the overarching ethnographic narrative. Through thick description, we illuminate participants' experiences in designing human-centered digital interfaces for deep space exploration, and how they conceive of user needs in relation to defining system requirements.

AN ANALYSIS OF HUMAN-CENTEREDNESS IN SPACE TECHNOLOGY

Prior work has pointed out the different, but complementary problem-solving approaches of systems thinking and design thinking [46], [47]. While at NASA, we were immersed in systems engineering projects striving to adopt a human-centered approach. We learned that systems engineers think of human-centered design as part of the solution space rather than the problem space. This was reinforced throughout our fieldwork in a variety of ways. For example, while working with the SUITS team, we observed that the engineers brought in designers to do the UI/UX work in creating a "slick" front-end for the system only after the features and functionality were determined so that the design and the build took place concurrently. Throughout the internship, we observed that many of the activities space engineers engage in are similar to human-centered design activities, such as writing scenarios and use cases to aid in defining system requirements. However, we found such scenarios lack the human-centered touch of incorporating insights derived from user research to model patterns of behavior. Unstructured interviews during fieldwork with the X-HAB team shed light on variations in attitudes among space engineers regarding human space exploration, revealing that while sending humans to space is a good thing because it, in the words of X-2, "justifies NASA's budget," humans in space are so risky and expensive, many space engineers may be more inclined to design and send robots instead.

In the following subsections, we present patterns in a space engineering culture that emerged throughout our fieldwork. We begin by describing the culture that dominated our viewpoint from within NASA and which seems to prevail within the broader space industry. We accomplish this in part by deciphering a key symbol that appears to unite space engineers with the engineering community as a whole, the Vee model. This finding suggests that established processes narrow engineers' focus to achieving technical excellence. Next, we consider groups both inside and outside of NASA and describe their efforts to adopt and implement a human-centered design approach, namely through human-systems integration. These groups are connected by the common cause of disrupting the established order and view this as necessary to hasten the adoption of human-centered design to meet NASA's mission to sustain an autonomous human presence beyond low Earth orbit. Finally, we consider challenges that emerge with respect to integrating HCI and HCD activities into the Vee model. This finding presents a closer looks at the tensions between employing an agile, iterative process within the larger context of an organization that leverages its history and traditions of a linear, waterfall process to resist change and negatively impacts the innovation that comes with it.

Culture of technology

Because most of the people studied throughout this fieldwork are trained as engineers, we were able to identify some common practices that many appear to take for granted. One such example that stood out as being particularly prominent among engineers in general, is the application of the Vee model (See [Appendix D](#) for the Vee model). The Vee is quite literally a V-shaped model which comprises steps in flowing down the requirements and designing the system on the left, then integrating the systems and verifying them on the right, culminating with the validation of the complete system on the top-right. As X-3 notes:

> *"You start at the beginning of the Vee, then you go down to feasibility. It's a very linear process. You just follow the Vee until it ends. Right, then downward, and then an upward kind of process. And the theory is that it leads to the least amount of cost overruns and mistakes because you've defined the system at such a level that you shouldn't have very many issues." ~ X-3*

Here we see the significance of the V-shape as illustrating the process of breaking down high-level human requirements into low-level systems requirements and assembling these components to build the system back up. The overarching concern of systems engineering is ensuring the system that gets built matches the vision of the stakeholders. This creates a technology-centered culture in which engineers are predominantly focused on technical optimization, or making the system work and extending the range at which it works. Consider this quote from SME-2, a leading space human factors investigator at NASA, about the space engineers they work with:

> *"They're very focused on making the thing work. And that's great because we need somebody focused on making the thing work, but that's where we play an important role to remind them about this other thing." ~ SME-2.*

And compare it to this quote from X-1, an undergraduate aerospace student preparing to enter the industry:

> *"I have been trained as an aerospace engineer, and our primary goal, at least the way we're taught, is to try and maximize the range that something can operate. Essentially, you try to work on increasing those ranges and you don't necessarily care about day to day operation because you need to design it and it has to work." - X-1*

Similarly, we find evidence of technology-centered culture constraining innovation just outside of NASA, in one of what is known as the Big Four, referring to Northrop Grumman, Boeing, Lockheed Martin, and Raytheon. Once requirements are defined, everything that comes out of the project must be traced back to them. This means that if user needs are not taken into consideration when writing requirements, they risk not being considered at all. Here X-4 provides an example of how working in the private space industry as an engineer building a system for NASA, is constrained to previously identified requirements:

> *"At work recently we were showing crew members through our CAD models and one of the things that struck me was how restrictive it is in terms of requirements. Like everything has to do with just meeting requirements, and sometimes there isn't money to come up with a nicer, more creative solution, so you're very limited in what you can do." ~ X-4*

In the Vee, decomposition continues until various elements of the system cannot be broken down any further. This is what is referred to as a "black box". In systems engineering, black boxes are those system elements in which the inner workings cannot be known. This concept yielded an interesting admission from X-3 who, when asked what the X-HAB team's earlier efforts were to understand the user, said somewhat sarcastically:

> *"Not much. They were like a black box. Our earlier efforts were very top-level." ~ X-3*

Later, we followed up with X-3 to elaborate:

> *"By black box, I mean we just wouldn't necessarily consider the user's emotional state. We were really just thinking about physical practicality. But a lot of how we think about the user is dependent on whether or not the user is considered a value to the design. And most space/aerospace stuff is trying to keep the user out of it, and then they have to adapt." ~ X-3*

Keeping the user out of it, and expecting them to adapt to the system is another common pattern of behavior we observed. CRASH is a non-crew-facing suite of tools that are designed to aid in trade study simulations which in turn will inform the design of crew-facing systems. Throughout the internship, we spent twenty-five percent of our time supporting human factors on CRASH. During a presentation of usability test findings and recommendations from the senior human factors engineers working on CRASH, the systems and software engineers alike made a habit of blaming the test participants for their inability to use the system. We observed one senior software architect interrupting each finding by loudly blurting out, "Training!" Recommendations to improve the interface were swiftly dismissed as being impossible or inappropriate given the level of development the project had already undergone. After a recommendation to improve contrast in support of legibility, another software engineer blamed the user's computer color settings and suggested we add a bullet point in the user manual indicating that they should adjust these settings when using CRASH for optimal performance. Although this project was touted during its System Requirements Review (SRR) as being human-centered and emphasizing the use of two human factors researchers, in practice CRASH predominantly still utilizes a technology-centered approach through the application of the Vee model and consults with human factors researchers primarily to test and validate the system. To further demonstrate the technical dominance of the engineers working on CRASH, during our internship, we contributed to upfront user research through a card sorting study for the latest addition to the CRASH suite of tools. This latest addition is billed as a collaboration hub. As it turns out, these tools are too complicated for the intended users to use them. To solve this problem, the CRASH team will train operators to handle service requests, and users can anticipate an average response time of three to six months.

Where upfront research is concerned in space engineering, such as when defining requirements, stakeholders make up a broad category that technically includes any human who has a hand in the system. Because of the technological-centeredness of space engineering culture, this can lead to ill-defined stakeholder groups in which engineers may mistake or neglect user needs in favor of meeting customer requirements. In their concept of operations, for example, when we first started research with the X-HAB team, the user of a voice interaction management system for the Lunar Gateway was broadly defined as NASA itself. Here we interpret this to mean that although such a system is intended for astronauts to interact with the autonomous systems aboard the Lunar Gateway, NASA appears to be defined as the user because the X-HAB team is delivering the system to NASA to use as it sees fit. However, we also witnessed this during the internship where, because human-centered resources were applied ad hoc, user research and usability tests were often used as an opportunity to gain further input and feedback from decision-makers rather than representative users.

The Vee used by our element of the Human Research Program may provide a rationale for this (see Appendix D). The Vee indicates that design is part of the solution space rather than the problem space. With this approach, we see that human-centered design does not begin until stakeholder requirements have been decomposed into system requirements, and technological feasibility has already been defined. If systems engineers think of the human user as a black box similar to how X-3 describes, in which only the physiological inputs and outputs can be known, then it would follow that user needs beyond those basic health and safety needs would not begin to be considered until system requirements reach this level. This would explain why clinicians are consulted when gathering stakeholder requirements instead of need assessment with representative users. Understanding this logic is important because, at NASA, systems engineering is described as a logical way of thinking [48]. As X-2 describes it, many space engineers already understand what an astronaut needs:

> *"It's kind of funny because most of us are avid space fans, so when we talk about researching what the astronauts need, we kind of already know." ~ X-2*

But X-4 had a different view from within the industry:

> *"The only way we think about user needs is from a personal perspective because they are usually not defined unless you're working specifically on HSI. So they're not in my requirements, my requirement is more like: The system needs this box. If the system needs the box, then somehow the crew needs the box, and I have to figure out the best place to put the box. But what the crew needs is not well defined." ~ X-4*

Given the technology-centeredness of systems engineering culture, when user needs are not considered upfront, they will likely not be considered unless they are shown to be a design flaw during testing, or as human error in operation. When it comes to teaming an astronaut with an autonomous system, this can present additional risk to crew health and safety as well as mission success. Choosing what tasks to automate and what tasks to burden the user with is an important design decision. This quote from SME-2 captures the tension between technology-centered and human-centered culture:

> *"I was in a meeting just a couple of hours ago asking questions and the answers I was getting back was that this is just how the system works. And they were showing me diagrams and architecture behind the scenes. I don't care about any of that, I care about what the crew is going to see and what they have to keep track of. Even after I convinced them of a couple of points*

where it would be better for automation to keep track of this thing, they said they couldn't change it because they don't have a requirement for it." ~ SME-2

To better understand how to design such a system, systems engineers write scenarios and create diagrams using something like the System Modeling Language, or SysML, to show how human users might interact with a system. These scenarios are often impersonal, referring to the user as "crewmember", and placing emphasis on fleshing out how the technology functions per requirements. While such scenarios go through several rounds of review before being approved to incorporate into the concept of operations, they are not based on user data, but rather reviewed and approved by clinicians. For example, while working with model-based systems engineers to conceptualize a medical system for long-duration missions, we were tasked with writing a caregiver as a patient scenario. On long-duration spaceflight, it is a requirement that a medical doctor will serve as a member of the crew. Here, systems engineers are tasked with investigating and mitigating risk with the system. In this case, as we learned, a risk that could negatively impact the success of the mission would be if the medical doctor became injured or otherwise incapacitated. How might such a medical system effectively support other crew members in providing sufficient medical care when the doctor is the patient? Having nothing to go on in terms of user research, and having just come from working with the X-HAB team on a voice assistant for the Lunar Gateway, we proposed voice interaction utilizing this system as well as a scenario in which the crewmember interacted with the system via the touchscreen on a tablet. Use of the voice assistant was rejected in review, in favor of a more sensible minimum viable product, e.g., the tablet interface. In this case, the voice interface, though being a hands-free option that would be of benefit to crewmembers trying to conduct just-in-time training while applying treatment, was seen as more of untested, fringe technology. Here again, we see a focus on catering to the system instead of putting the human at the center. SME-2 described a major technological challenge of extended missions beyond low Earth orbit and NASA's solution:

"We know these laptops and tablets going on Gateway are going to die after prolonged exposure to radiation, but they're cheaper, so our [NASA] plan is to send replacements, and then the astronauts are just going to have to reboot." ~ SME-2

When characterizing the collaborative efforts between systems engineers and clinicians to design candidate medical systems, SME-3 described the emphasis being on the little details. Mass and volume have to be carefully calculated with variations in supplies, so trade studies must be run to determine the optimal amount of each supply. In this regard, the emphasis is not on the critical incidents that have a low probability of occurring, but rather on making sure crews are sent into space with just enough medicine to prevent renal stone formation, enough headache medicine to keep crews productive, and just enough band-aids to ensure the minor cuts and scrapes crews are known to endure do not become something more serious. In human space exploration, every additional day a crew can spend in space beyond low Earth orbit is maximizing and extending the range that the system as a whole can operate.

Toward human-centeredness

There are, however, groups of people both inside and outside of NASA seeking to improve human-centered maturity in space technology. And some of these efforts are having a positive impact. Human systems integration (HSI) practitioners have adapted a human-centered approach to the systems engineering process. NASA facilitates several programs as design challenges, like SUITS and X-HAB, to generate a more diverse array of ideas. We also observed teams within NASA proudly going against the grain of the waterfall model in adopting a sprint-driven iterative approach typical of human-centered design processes. Younger space engineers tend to display an eagerness to adopt the human-centered design trends and processes that proliferate in the broader technology industry. And successes in emphasizing a more human-centered approach in newer space companies like SpaceX and Blue Origin are bringing in a different perspective, as noted by SME-2 and X-3:

> *"Where it's gotten really interesting is that NASA is now working more closely with the commercial crew providers like SpaceX, Boeing, and Northrop Gruman that are challenging the status quo at NASA. Whereas we might be slow to change because we were successful in doing something with the shuttle program or on the ISS, these companies are actively looking for better solutions." ~ SME-2*

> *"NASA hasn't always been the most ergonomically friendly. They would stick an astronaut in a can if it works. The same thing with the Russians, like the Soyuz, you're basically stuffing them into this really cramped space. But now we're seeing SpaceX and some other companies starting to embrace this more user-centric approach." ~ X-3*

According to SME-2, NASA has long been proponents of human-centered design, which is written into a lot of documentation. They also admit that while there are still a lot of teams that probably do not use human-centered design, there is a growing recognition of the positive impact it has on the systems engineering process:

> *"A lot of our programs now take advantage of our human systems integration working group. A lot of teams are actively involving an HSI role in their projects. Now we have all these forums and other mechanisms to spread the word about human-centered design and other related topics." ~ SME-2*

At NASA, SME-1 describes their efforts to shift perceptions of human-centered design away from just the solution space and into the problem space through user research:

> *"From the perspective of HCI, we also do research. When I started engaging more in this domain, I was really pushing for more research in the area of HCI so that we can continue tackling the more cutting edge tasks and infuse human factors into future operations." ~ SME-1*

SME-1 goes on to discuss their experience involving the importance of a human-centered approach:

> *"We find that if we do engage the end-users, and successfully convince our stakeholders that this process is valuable, you end up with a better tool. I have seen time and time again that it is a*

> *successful process. Designing and implementing software without that context, the resulting software is brittle and requires continuous maintenance, which doesn't even exist in continuous development." ~ SME-1*

Every project we worked on within NASA was defined as operating within a human-centered approach. Our mentor was one of the contributing authors to the Human Systems Integration Handbook. The most readily identifiable method denoting HCD that we observed concerning these projects is that of the agile approach. During the SRR for CRASH, the use of the agile process was emphasized as being human-centered and running counter to the more traditional process at NASA as, "Waterfall to the T." Here again, we see the invocation of the Vee model which, according to Boy, is an extension of the waterfall model of software development [49] (See Appendix E for the Waterfall model). Projects like CRASH are paving the way forward towards a more human-centered NASA.

Some teams within NASA want to explore the feasibility of an idea of use of technology without having to commit the resources necessary to do it themselves. To stimulate such innovation, NASA's solution has been to build relationships with universities through Academic Innovation challenges like X-HAB and SUITS. When asking members from the SUITS and X-HAB teams what value they felt that students brought to NASA through university challenges, the most common response was free labor. According to these teams, NASA stakeholders benefit from quickly soliciting divergent ideas without having to spend time and effort to generate them internally. X-3 describes the common perception the X-HAB team shared regarding the purpose of the X-HAB challenge:

> *"What NASA does with the X-Hab challenge is they take university students and have them do a lot of this preliminary research on basic feasibility studies. Like talking about our project this year, is voice control on a space station something we would even want to pursue in the future?" ~ X-3*

S-1 similarly describes SUITS as a means of soliciting a range of ideas:

> *"When we went to Houston to present our system at JSC, the researchers were pretty much just taking notes on the different teams' presentations. It seemed like a way for them to rapidly prototype without having to provide the resources for it." ~ S-1*

In recent years, particularly following the official announcement of the Artemis program in 2019 [50], the focus of these challenges has become increasingly human-centered. Both the SUITS and the X-HAB teams displayed an interest in developing human-centered projects in their written proposals. Both teams leveraged the expertise of a retired astronaut with experience conducting missions on the International Space Station, as well as other industry contacts they had made both through faculty advisors as well as subsequent years of working with NASA on technical projects. During the SUITS 2020 challenge, NASA provided teams the opportunity to gain insights from subject matter experts through monthly web presentations. The SME would give a short presentation on a related topic followed by a Q&A session which afforded all teams the opportunity to ask questions and benefit from the responses provided to other team's questions. The SUITS team typically made an evening of it. Before social distancing as a public health and safety measure, core members of the SUITS team would throw watch parties. Presenters included both current and former astronauts, planetary scientists, and HSI researchers. Notes were taken in a shared, collaborative document so those insights could be collectively consumed, promoting alignment on new findings.

On the SUITS team, we used this data to create user personas by employing an approach referred to as provisional, or ad-hoc personas [51], [52] (See Appendix F for one of our design personas). This involved synthesizing data gathered from the web presentations with brief profiles of all the recently named Artemis generation astronauts. During fieldwork with the X-HAB team for the 2021 challenge, our project emphasized the use of design personas in a different way. The team had proposed to develop a voice interaction management system to work with the NASA Platform for Autonomous Systems (NPAS). This project was situated in the context of enabling crew members to interact with the Lunar Gateway, a modern space station set to orbit the Moon and eventually serve as an outpost and launchpad to send crews to Mars. As the team began conducting preliminary research into what was needed to design such a system, we soon learned about the importance of designing the personality of a voice interface. When designing interfaces that rely on voice interactions, there is an added challenge of designing a system personality to support interaction through establishing a relationship built on trust, so that the human and the system can function together as a team [53]–[55]. We led the X-HAB team, composed primarily of space engineers, through the process of creating a system persona to effectively support crew interactions on Gateway. Through a series of brainstorming and dot voting activities aimed at engaging the X-HAB team in human-centered design through the Double Diamond design model (See Appendix G for the Double Diamond model), we exposed and challenged assumptions team members had about astronaut users. One such assumption the X-HAB team collectively found interesting, was the consideration for psychological well-being. Discussing it with the team, we learned that after spending the majority of 2020 in relative isolation, team members expressed greater empathy for the isolation astronauts experience in space, which manifested in the form of greater effort being applied to supporting that need with the system.

Using this information, the X-HAB team expressed enthusiasm for the adoption of the human-centered design approach:

> *"Honestly, what myself and everyone else, including our stakeholders at NASA, has been saying is how lucky we have been to have an HCI expert on the team to encourage us to use human-centered design. We would have come up with something, but I don't think it would be anywhere near as in-depth as what we've been able to accomplish using HCD." ~ X-2*

During the X-Hab team's Preliminary Design Review (PDR), one such NASA stakeholder reviewing our progress noted how different our human-centered approach and the ideas that came out of it were in comparison to other teams within the agency (NASA) upon which they sit related to trusted autonomy. They went on to note how refreshing it was to have a different approach, and about the author, commented on how they believed this was a reflection of the diversity of the team. We know this comment was about the author because everyone else on the team was in space/aerospace engineering, except for one applied physicist. This led to our ultimate finding during fieldwork with the X-HAB team, that space engineers may excel at incorporating human-centered design.

This finding is shared by the X-HAB team's NASA stakeholders. While they did not explicitly use the words "human-centered", they did express an enthusiasm for having younger engineers designing interfaces. This is because, according to them, younger engineers had grown up with video games and other modern technologies, as confirmed by X-1:

> *"Last year, they would talk a lot about how they wanted a generation that had grown up with video games and iPhones to design the interfaces for everyone." ~ X-1*

Challenges

Despite these efforts and successes in applying more human-centered approaches, challenges remain, and much can be improved. While there is an acknowledgement that more modern technologies and approaches to designing them are necessary for the future of human spaceflight, past successes can serve to disincentivize in-house exploration of innovative solutions:

> *"I think, at least in my experience, the reason that most people don't accept it at NASA is that they don't believe there's a benefit. A lot of times NASA has a perspective of like, if it ain't broke, don't change it." ~ SME-1*

> *"We are constantly battling the mindset of this is how we've always done it. This is how Shuttle did it, this is how ISS did it. Which can be a good thing in terms of safety in order to express a high level of confidence. But sometimes we have to question whether or not we need to go that route." ~ SME-2*

From our informants, we frequently heard NASA described as slow. Not only in adopting new processes, but even simply in making use of their resources. In October of 2020, NASA stakeholders informed the X-HAB team they were getting software licenses to build their voice assistant using G2:

> *"Just from past experience, we knew that NASA can be slow at responding for things. Knowing that ahead of time, we kind of gave them a deadline of if we didn't get the licenses by the SDR, we were going to look for other options." ~ X-2*

Regarding the innovative ideas coming from university teams like X-Hab and SUITS, there is a challenge in merging them back into NASA:

> *"I always felt that the work on the X-Hab challenge was more free than it is now that I'm a professional in the industry. Like, now I can't go explore something in VR because everything is a monetary decision. So I think NASA appreciates the open-ended creativity, but I always felt like after we were done with our projects and delivered our paper, they didn't go anywhere." ~ X-4*

> *"In some ways, it's a lot of value because NASA is a government agency and sometimes it's very hard to do innovative things. Engaging students allows us to be a little more open-ended and also*

just bring in new ideas. And so from that perspective, there's a lot of value. The reason why I say it's hard is that because those ideas are innovative, they are really hard to merge back into NASA. Like, we very much want to grow, but we can be held back by bureaucracy and red tape." ~ SME-1

During the NASA internship, we experienced firsthand how slow the organization can be as a result of such bureaucracy. While our supervisor was elated to learn that we had received our NASA laptop before the first day of work, something they noted had never happened before, we spent the first month of the internship reminding the IT team that they needed to install a specific piece of software before we could begin work. Another piece of software, specifically a design tool required for a key deliverable our supervisor recruited us for, was never installed throughout the four-month internship. Strict limitations on software create a prohibitive environment for design activities. Prototypes have to be hardcoded, slowing iterative cadence and increasing effort among the development team. For example, when participating in a usability test for CRASH, we were forced to take remote control of the facilitator's computer through a Teams virtual meeting screen to interact with the prototype they had installed on their computer.

The CRASH usability test brings up another challenge to implementing a human-centered approach, which is a tendency to recruit non-representative users. Recruiting other engineering students outside of the project to test prototypes for the X-HAB and SUITS challenges may not be ideal, but in terms of feasibility, this is often as close as such teams will get to representative users. At the start of the internship, we knew part of our time was to be spent working on CRASH, so when our supervisor offered us up as a candidate for usability testing, we assumed this was for pilot testing with an added bonus of getting familiar with the system. However, our data were included in the presentation of the findings discussed in the earlier subsection.

User researchers struggle with recruiting representative users at NASA for a variety of reasons. As we previously mentioned, sometimes the actual user group is ill-defined, as in the case of the model interfaces we designed. Also, given that NASA is a government agency conducting internal tests, it was our experience that researchers were unable to incentivize participation in user research. On top of this, because of NASA's dominant engineering culture, quantitative metrics and scientific rigor prevail. This creates tension with regard to the implementation of more innovative human-centered techniques and activities that rely more heavily on non-linear methods, qualitative data. To use the CRASH usability test as a further example, the test itself was two hours long, spread out across two different tools within the CRASH suite, and accompanied by extensive questionnaires to calculate cognitive loading and the system usability score (SUS). This finding was reinforced by SME-1, who in contrast to our experience with CRASH, conducts smaller, more frequent rounds of usability testing:

"We also do usability testing at scale. I've seen some people do very large usability studies. And they're trying to do statistics on dozens of users. My team's stance is that we just need a small-scale iteration to get feedback about, so we get five people to use them to get feedback." ~ SME-1

This lack of current knowledge regarding current tools and practices in HCI seems to extend to an out-of-date understanding of HCI theory as well [56]. Almost as ubiquitous as the Vee model was Miller's 1956 model of human information processing [57]. In our fieldwork, this model was first mentioned by a member of the X-HAB team, and later during the CRASH presentation where the senior human factors researcher references Miller's model in justifying the human-centered approach of the project. As another example, SME-2 describes a challenge in designing for astronaut autonomy:

> *"Designing for autonomy means making things simple, not trying to build too much complexity. Right now what the crew tends to like, and these developer groups want to do is put everything you need on the display, and it gets very cluttered and hard to read. We need to think about clever ways to have all the information available as needed while only showing them what's needed for the task at hand." ~ SME-2*

DISCUSSION

The analysis in the previous section yielded new empirical findings about the conception and implementation of human-centered design in projects predominantly supported through technology-centered engineering. It further described efforts to disrupt and improve the application of HCD in NASA's Human Research Program despite the many challenges that remain. While our findings suggest that a systems engineering skill set can be an advantage in the application of human-centered design, this advantage hinges on resources for user research being allocated up front prior to requirements writing. This allows teams to gather insights not only into user needs, but also their desires, motivation, behaviors, etc. Leveraging a range of insights such as these are useful in empathizing with the human user and having a better understanding of how to design for them.

Astronaut autonomy

Supporting astronaut autonomy is of increasing interest and importance to the burgeoning space industry as NASA seeks to establish and sustain a presence on the Moon. This notion of supporting autonomy is situated along two different dimensions as relevant to the field of HCI. "Smart" technologies must achieve a level of autonomous operations so that they can be successfully partnered with an individual astronaut or crew. This level of autonomous operations will enable the human-autonomy team to effectively replace the flight controllers and subject matter experts who currently provide real-time guidance and make nearly all mission-related decisions for crews in space. The other dimension refers to digital interfaces to support human information processing through the promotion of good user experience design. With these two dimensions aligned, astronauts will be able to make informed decisions and maintain productivity to successfully carry out missions to advance deep space exploration.

Although Olson unpacks the symbolic meaning of 'X' in the space industry as that of the 'extreme' [58], in our study we found it to be rather straightforward in symbolizing 'exploration'. This can be seen in SpaceX (Space Exploration Technologies Corp.), eXploration Habitat (X-HAB), ExMC (Exploration Medical Capability), etc. However, while Olson and others have made similar observations to this study regarding a NASA culture that is dominated by technology-centered engineering [22], [23], [46], [49], [58]–[60]; what resonates with the American culture, the humans that fund NASA, is the human exploration of space as the final frontier. As former President George W. Bush unveiled his vision for space exploration he said, “This cause of exploration and discovery is not an option we choose; it is a desire written in the human heart,” [61]. Within the broader literature on human space exploration, allusions to the human spirit and desire to endure great risk for the sake of exploration proliferate [62]–[64]. Humans decide to go to space and convince other humans to join them in this effort. Entire nations of people have rallied around the idea that humans in space are good. One of the subject matters experts whom we worked closely with mentioned that they had only recently joined NASA in the past year despite a long career in the field. Upon receiving the offer, they spoke to their boss at the time who encouraged them to take the position saying, “NASA is the reason we became systems engineers.” Space exploration is inherently human-centered.

As Olson described it, in an extreme environment such as space, the very habitat becomes a kind of ‘cyborg epidemiology’ [58]. With regard to habitat design, Balint invoked Maslow’s Hierarchy of Needs to argue for a more human-centered approach to habitat design [60], saying the initial focus should be on fulfilling the higher-level need of self-actualization, and that the more basic psychological and physiological needs would follow. Similar to what we found during this fieldwork, Balint notes that NASA’s approach to human-centeredness revolves around fulfilling basic, low-level needs. Buchanan argues that while systems thinking conceptualizes systems and ends with an order for design action, design thinking starts with creative inquiry and ends with the creation of systems [47]. Although we found innovation within NASA both a challenge as well as a pressing concern, we recognize that issues related to HCI are design problems rather than engineering problems, and should be treated as such. Like Balint, we argue that Maslow’s Hierarchy of Needs could be flipped upside down so that designers, engineers, and other stakeholders can explore the problem space and solution space iteratively, and start by accommodating higher-level needs. Design implications derived from such a concept should seek to illuminate self-actualization and meaning-making of living and working in space. The purpose of this is to levy an eye toward the future, where space is a place of work. The technology-centered engineering culture of NASA is predominantly driven by meeting requirements related to basic human needs, those of health and human safety. But NASA does have historical precedence of successfully incorporating human-centered design for self-actualization to make the habitat more comfortable [65].

An emerging role for HCI in space technology

Human-centered design and HCI opportunities in space technology extend beyond direct support of astronaut autonomy, as NASA itself is in need of human-centered disruption and innovation with regard to IT and computer supported cooperative work. And this remains the case across the spectrum of HCI paradigms [10]. The challenges posed by circumstances of crewed deep space exploration and the CSCW required to accomplish such complex, interdisciplinary projects should resonate among many in the field. Such challenges not only involve shaping the direction of human-computer interfaces for space travel and exploration, but in helping to improve the human-centered work processes of the engineers conceptualizing and building these systems. This latter challenge encompassed our internship within NASA which began in January of 2021. As mentioned in our findings, during the CRASH SRR presentation, a space engineer touted the team's success in utilizing a human-centered approach along with an agile process, highlighting the challenges in doing so within NASA, which they described as being, "Waterfall to a T." Guy Boy describes the Vee as an extension of the waterfall process and notes its widespread use across the spectrum of engineering disciplines [49]. Boy observes that most problems in the validation phase come from a lack of human-centeredness or organizational-centeredness in the requirements. This is the flaw of technology-centered engineering, where systems engineers conceptualize a system, software engineers build the system, then human factors engineers reduce the probability or rate of human error to acceptable limits. Boy's model of human-systems integration reinforces our findings that putting the user first not only reduces risk but is cheaper and ultimately results in a better product that requires less training and maintenance (See Appendix H for Boy's model of Human-System Integration) .

What HCI can offer is a greater return on investment. Through more user research, rapid prototyping, and a larger volume of design iterations up front, we can create a more viable product before a single line of code is written. The parallels between systems engineering and HCI are evident. The Vee model outlines how engineers gather requirements, design a system to meet them, build the system, then validate the system. The design thinking process similarly outlines steps to empathize, define, ideate, prototype, and test. Greene compared the historical context and evolution of engineering systems thinking and design thinking as complementary approaches to systems engineering and design [46]. The primary difference between these two approaches is that of exploration. As our informants suggest, the Vee is a very logical, orderly, and linear process. Oftentimes the design thinking process comes with the disclaimer that it is not a linear process. When designers are allowed to explore the problem space instead of being constrained to the solution space, human-centered design can proliferate. We observed space engineers display some skill in incorporating a human-centered design approach in actually personifying their system to better support the user.

There are some limitations regarding the study. We engaged in only twelve semi-structured interviews across three field sites over a year. A year that was unordinary, to say the least, concerning the global COVID pandemic rendering all work remote. We would have liked to conduct interviews with more people as well as more follow-up interviews. However, given the difficulty we experienced in recruiting for interviews, we felt that pushing for more would have put unnecessary strain on the rapport we had built with members of these working groups. Instead, we relied more on unstructured interviews and observation, learning by doing and creating opportunities to gain relevant insights in the spur of the moment. We believe that our findings are sound about systems engineering in the space industry, but that no broad generalizations can be made of systems engineering or engineering in general, especially outside of the space industry.

In terms of future work, we outline some areas in which we believe an emerging role for HCI in supporting astronaut autonomy will be most prominent.

- **CSCW, and the future of work:** In the future, many people will work in space. The recent stretch of remote work has provided insights into the rudimentary kinds of human problems we might expect to face in the future where computer-supported collaborative work will eventually extend across the solar system. Conducting more exploratory research will be necessary to lay the foundation and take lessons learned concerning CSCW on Earth, and improve upon them in space.
- **Design systems for human-autonomy teaming:** Consistency, standardization, and reusability are key to promoting good usability and a positive user experience. In recent years, design systems have become relatively ubiquitous in the technology industry. Such design systems promote an agile cadence through user-validated design elements accompanied by clean code snippets to speed development. Design systems further help to reduce disagreements between designers and developers by serving as the single source of truth.

It is important to remember that careful design considerations must be made upfront. Once humans adapt to a certain interaction pattern or technological device, it becomes more difficult to introduce something drastically different, even if it offers a substantial improvement on the surface. Another opportunity for future work would be to explore cultural transmission in isolated pockets of human environments in space as national and international space habitats begin to proliferate on and around the moon as well as Mars. This will be important in better understanding how humans adapt to extreme environments in the socio-cultural context.

CONCLUSION

This thesis presented findings from a fifteen-month ethnographic study of how systems engineers conceptualize the user experience and use it to justify design decisions about supporting astronaut autonomy. Data collection revolved around participant observation, unstructured and semi-structured interviews, and team data sharing. All of these sources were integrated for analysis via grounded theory and self-reflection.

Contributions of this work include (1) empirical research in technology-centered cultures for human-centered design; (2) descriptions of efforts and impact in propelling human-centered design-forward within NASA; (3) descriptions of some challenges that remain. We believe this research opens up a range of future work engaging with astronautics programs and internal digital transformation efforts for the sake of supporting astronaut autonomy and promoting the eventual expansion of humans throughout the solar system.

REFERENCES

[1] M. Smith *et al.*, "The Artemis Program: An Overview of NASA's Activities to Return Humans to the Moon," in *2020 IEEE Aerospace Conference*, 2020, pp. 1–10.

[2] B. Whitworth and A. Ahmad, *The social design of technical systems: Building technologies for communities*. The Interaction Design Foundation, 2014.

[3] N. Kanas, "Autonomy and the crew–ground interaction," in *Humans in space*, Springer, 2015, pp. 99–107.

[4] D. J. Leach, T. D. Wall, S. G. Rogelberg, and P. R. Jackson, "Team autonomy, performance, and member job strain: Uncovering the teamwork KSA link," *Applied Psychology*, vol. 54, no. 1, pp. 1–24, 2005.

[5] K. Holden, N. Ezer, and G. Vos, "Evidence report: Risk of inadequate human-computer interaction," 2013.

[6] S. Hillenius, "Designing interfaces for astronaut autonomy in space," 2015.

[7] S. Harris and B. Simpson, "Human Error and the International Space Station: Challenges and Triumphs in Science Operations," in *14th International Conference on Space Operations*, 2016, p. 2406.

[8] P. C. Schutte, "How to make the most of your human: design considerations for human–machine interactions," *Cognition, Technology & Work*, vol. 19, no. 2, pp. 233–249, 2017.

[9] B. ISO and B. STANDARD, "Ergonomics of human-system interaction," 2010.

[10] S. Harrison, D. Tatar, and P. Sengers, "The three paradigms of HCI," in *Alt. Chi. Session at the SIGCHI Conference on human factors in computing systems San Jose, California, USA*, 2007, pp. 1–18.

[11] H. Beyer and K. Holtzblatt, "Contextual design," *interactions*, vol. 6, no. 1, pp. 32–42, 1999.

[12] A. Hashizume and M. Kurosu, "Understanding user experience and artifact development through qualitative investigation: ethnographic approach for human-centered design," in *International Conference on Human-Computer Interaction*, 2013, pp. 68–76.

[13] R. L. Baskerville and M. D. Myers, "Design ethnography in information systems," *Information Systems Journal*, vol. 25, no. 1, pp. 23–46, 2015.

[14] M. Galindo, C. Martinie, P. Palanque, M. Winckler, and P. Forbrig, "Tuning an HCI curriculum for master students to address interactive critical systems aspects," in *International Conference on Human-Computer Interaction*, 2013, pp. 51–60.

[15] U. Farooq and J. Grudin, "Human-computer integration," *interactions*, vol. 23, no. 6, pp. 26–32, 2016.

[16] G. Schirner, D. Erdogmus, K. Chowdhury, and T. Padir, "The future of human-in-the-loop cyber-physical systems," *Computer*, vol. 46, no. 1, pp. 36–45, 2013.

[17] E. Lloyd, S. Huang, and E. Tognoli, "Improving human-in-the-loop adaptive systems using brain-computer interaction," in *2017 IEEE/ACM 12th International Symposium on Software Engineering for Adaptive and Self-Managing Systems (SEAMS)*, 2017, pp. 163–174.

[18] S. Huang and P. Miranda, "Incorporating human intention into self-adaptive systems," in *2015 IEEE/ACM 37th IEEE International Conference on Software Engineering*, 2015, vol. 2, pp. 571–574.

[19] N. A. Stanton and M. S. Young, "Vehicle automation and driving performance," *Ergonomics*, vol. 41, no. 7, pp. 1014–1028, 1998.

[20] J. D. Lee and K. A. See, "Trust in automation: Designing for appropriate reliance," *Human factors*, vol. 46, no. 1, pp. 50–80, 2004.

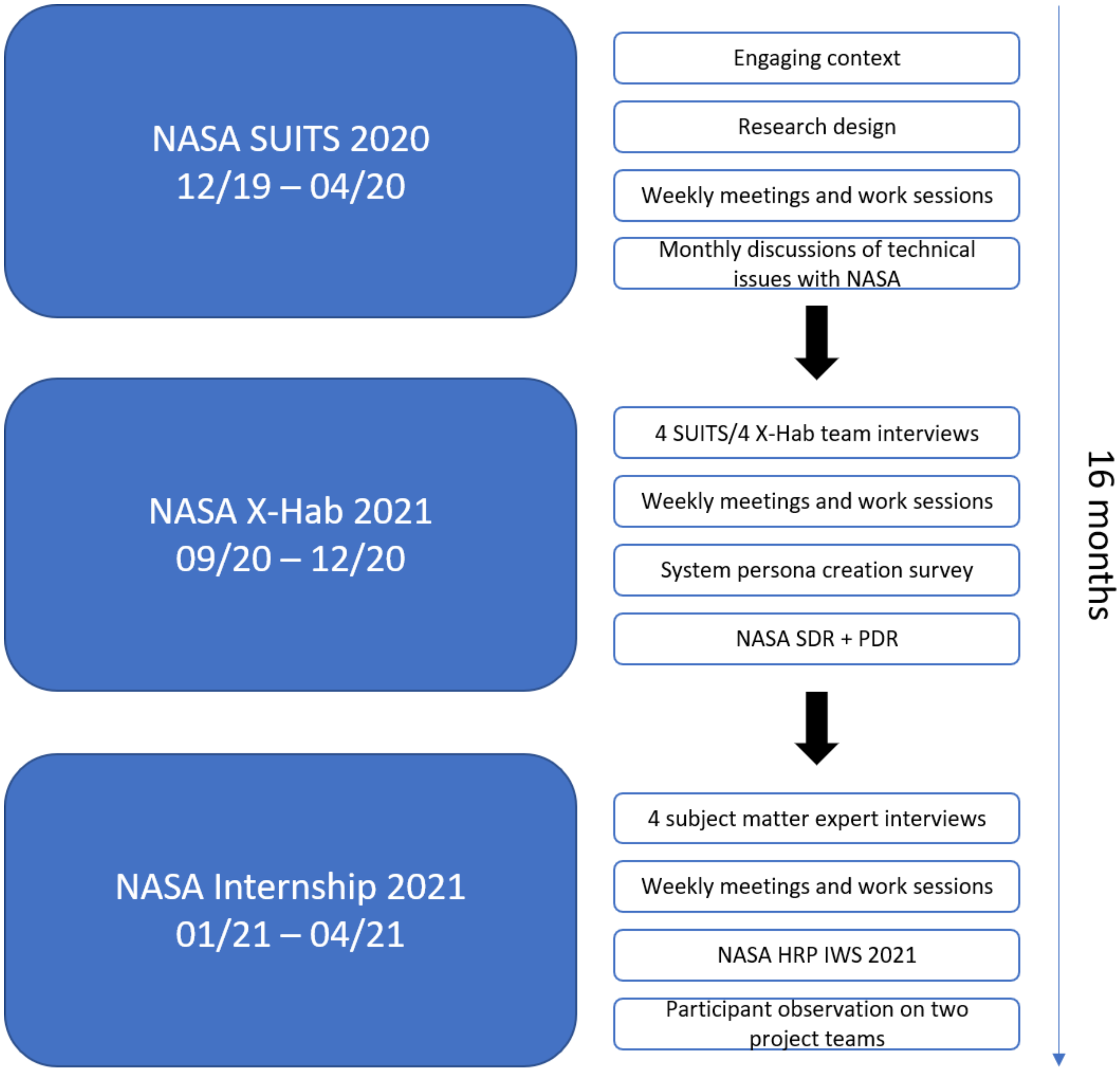
[21] M. Gil, M. Albert, J. Fons, and V. Pelechano, "Designing human-in-the-loop autonomous Cyber-Physical Systems," *International Journal of Human-Computer Studies*, vol. 130, pp. 21–39, 2019.

[22] K. H. Abbott and P. C. Schutte, "Human-centered automation and AI-Ideas, insights, and issues from the Intelligent Cockpit Aids research effort," 1989.

[23] C. Graeber and C. E. Billings, "Human-centered automation: Development of a philosophy," 1990.
[24] C. E. Billings, *Human-centered aviation automation: Principles and guidelines*. National Aeronautics and Space Administration, Ames Research Center, 1996.
[25] T. C. Eskridge, D. Still, and R. R. Hoffman, "Principles for human-centered interaction design, Part 1: Performative systems," *IEEE Annals of the History of Computing*, vol. 29, no. 04, pp. 88–94, 2014.
[26] P. C. Schutte, "Wings: A new paradigm in human-centered design," 1997.
[27] F. Figueroa, L. Underwood, B. Hekman, and J. Morris, "Hierarchical Distributed Autonomy: Implementation Platform and Processes," in *2020 IEEE Aerospace Conference*, 2020, pp. 1–9.
[28] D. D. Woods, "Learning From Automation Surprises and 'Going Sour,'" *Cognitive engineering in the aviation domain*, p. 327, 2000.
[29] N. B. Sarter, D. D. Woods, and C. E. Billings, "Automation surprises," *Handbook of human factors and ergonomics*, vol. 2, pp. 1926–1943, 1997.
[30] D. E. Cooke, "An overview of NASA's intelligent systems program," in *2001 IEEE Aerospace Conference Proceedings (Cat. No. 01TH8542)*, 2001, vol. 7, pp. 7–3664.
[31] E. Smith, "Intelligent systems technologies for ops," in *SpaceOps 2012*, 2012, p. 1294820.
[32] J. Zhang, V. L. Patel, K. A. Johnson, and J. W. Smith, "Designing human-centered distributed information systems," *IEEE intelligent systems*, vol. 17, no. 5, pp. 42–47, 2002.
[33] T. S. Balint and P. Pangaro, "Design space for space design: Dialogs through boundary objects at the intersections of art, design, science, and engineering," *Acta Astronautica*, vol. 134, pp. 41–53, 2017.
[34] T. S. Balint and C. H. Lee, "Pillow talk—Curating delight for astronauts," *Acta Astronautica*, vol. 159, pp. 228–237, 2019.
[35] M. N. Russi-Vigoya *et al.*, "Supporting Astronaut Autonomous Operations in Future Deep Space Missions," in *International Conference on Applied Human Factors and Ergonomics*, 2020, pp. 500–506.
[36] G. Salazar, "Development Considerations for Implementing a Voice-Controlled Spacecraft System," in *2019 IEEE International Symposium on Measurement and Control in Robotics (ISMCR)*, 2019, pp. B3-1-1-B3-1–20.
[37] J. J. Marquez, S. Hillenius, B. Kanefsky, J. Zheng, I. Deliz, and M. Reagan, "Increasing crew autonomy for long duration exploration missions: self-scheduling," in *2017 IEEE Aerospace Conference*, 2017, pp. 1–10.
[38] H. R. Moses, "Perspectives from the Wearable Electronics and Applications Research (WEAR) Lab, NASA Johnson Space Center," 2017.
[39] J. Blomberg and H. Karasti, "Reflections on 25 years of ethnography in CSCW," *Computer supported cooperative work (CSCW)*, vol. 22, no. 4–6, pp. 373–423, 2013.
[40] H. R. Bernard, *Research methods in anthropology: Qualitative and quantitative approaches*. Rowman & Littlefield, 2017.
[41] L. A. Suchman, *Plans and situated actions: The problem of human-machine communication*. Cambridge university press, 1987.
[42] C. Wasson, "Ethnography in the field of design," *Human organization*, pp. 377–388, 2000.
[43] A. Crestadoro, *The Art of Making Catalogues of Libraries: Or, a Method to Obtain in a Short Time a Most Perfect, Complete, and Satisfactory Printed Catalog of the British Museum Library*. Literary, Scientific & Artistic Reference Office, 1856.
[44] M. A. K. Halliday and C. Yallop, *Lexicology: a short introduction*. A&C Black, 2007.
[45] C. Urquhart, H. Lehmann, and M. D. Myers, "Putting the 'theory'back into grounded theory: guidelines for grounded theory studies in information systems," *Information systems journal*, vol. 20, no. 4, pp. 357–381, 2010.
[46] M. Greene, R. Gonzalez, P. Papalambros, and A.-M. Mcgowan, *Design Thinking vs.*

Systems Thinking for Engineering Design: What's the Difference? 2017.
[47] R. Buchanan, "Systems thinking and design thinking: The search for principles in the world we are making," *She Ji: The Journal of Design, Economics, and Innovation*, vol. 5, no. 2, pp. 85–104, 2019.
[48] S. R. Hirshorn, L. D. Voss, and L. K. Bromley, "Nasa systems engineering handbook," 2017.
[49] G. A. Boy, *Human–systems integration: from virtual to tangible*. CRC Press, 2020.
[50] K. Chang, "For Artemis Mission to Moon, Nasa Seeks to Add Billions to Budget," *The New York Times*, 2019.
[51] A. Cooper, "The Inmates are Running the Asylum," in *Software-Ergonomie'99*, Springer, 1999, pp. 17–17.
[52] D. Norman, "Ad hoc personas & empathetic focus," *The persona lifecycle: Keeping people in mind during product design*, pp. 154–157, 2006.
[53] R. Dasgupta, R. Dasgupta, and Srivastava, *Voice User Interface Design*. Springer, 2018.
[54] M. H. Cohen, M. H. Cohen, J. P. Giangola, and J. Balogh, *Voice user interface design*. Addison-Wesley Professional, 2004.
[55] C. Pearl, *Designing voice user interfaces: principles of conversational experiences*. O'Reilly Media, Inc., 2016.
[56] N. Cowan, "The magical number 4 in short-term memory: A reconsideration of mental storage capacity," *Behavioral and brain sciences*, vol. 24, no. 1, pp. 87–114, 2001.
[57] G. A. Miller, "The magical number seven, plus or minus two: Some limits on our capacity for processing information.," *Psychological review*, vol. 63, no. 2, p. 81, 1956.
[58] V. A. Olson, "American extreme: An ethnography of astronautical visions and ecologies," 2010.
[59] C. E. Billings, *Human-centered aircraft automation: A concept and guidelines*, vol. 103885. National Aeronautics and Space Administration, Ames Research Center, 1991.
[60] T. Balint, *Design Space for Space Design: Humanly {S: pace} Constructs Across Perceptual Boundaries*. Royal College of Art (United Kingdom), 2016.
[61] G. S. Hubbard, "Humans and robots: Hand in grip," *Acta Astronautica*, vol. 57, no. 2–8, pp. 649–660, 2005.
[62] S. O'Keefe, "The vision for space exploration," *National Aeronautics and Space Administration*, 2004.
[63] B. R. Finney, "Anthropology and the Humanization of Space," *Acta Astronautica*, vol. 15, no. 3, pp. 189–194, 1987.
[64] J. A. Dator, *Social foundations of human space exploration*. Springer Science & Business Media, 2012.
[65] R. Loewy and W. Snaith, *Habitability Study, Earth Orbital Space Stations: Final Report*. Washington, DC: NASA, 1972.
[66] Peter Kemp & Paul Smith, *Waterfall model*. [Online]. Available: https://commons.wikimedia.org/w/index.php?curid=10633070
[67] D. Council, "The 'double diamond'design process model," *Design Council*, 2005.

APPENDIX A - Timeline of Fieldwork



APPENDIX B - General Interview Protocol

Warm-up

1. Can you tell me a little about your academic/professional background?
    a. What kind of skills do you gain in this kind of discipline?
        i. So [x, y, z] are all hard skills, now can you take a moment to describe some of the soft skills you're developing through your academic program?
            1. Can you tell me about a recent experience where these soft skills were either put to the test, or on full display?
    b. What career path are you planning to pursue?

        i. Do you feel that you're being adequately prepared for this career through your academic program and internship experience?
        ii. Any specific companies you are hoping to work for?
2. Can you tell me your story about how you first became interested in space?
    a. What motivated you to pursue projects/careers follow-up in human spaceflight technologies?
3. What is your role in [TEAM]?
    a. What are the responsibilities involved in this role?

Main Interview

- Could you describe the first NASA X-Hab/SUITS Challenge that you participated in as a member of [TEAM]?
    - How did you hear about this challenge?
    - What problem is NASA trying to solve with this challenge?
        - What value do university teams bring to NASA with the X-Hab challenge?
    - Can you tell me who you've worked with from NASA?
    - Who have you met?
- Could you break down the process that [TEAM] follows to contribute to the X-Hab/SUITS challenge?
    - Is this process taught in any of your program's courses?
    - Who worked on what?
    - What were the most challenging components?
        - How did you manage these challenges?
        - Could you describe how you identified what was needed to make the system useful to NASA?
            - Can you tell me more about how systems engineers assess risk?
        - Who helped you?
            - What did they do?
    - What are the components of the project that you were most drawn to?
        - Why?
        - Were these easier because of your interest level?
        - Who else was drawn to these aspects of the project?
- Could you describe how you come to understand how to support astronauts in space?
        - How did the group figure out how to make a good UX?
    - What resources do you use?
    - Who do you talk to?
        - What is their level of understanding?
    - How do aerospace/space engineers think of user needs, preferences, and comforts?
            - Is there a certain sort of process engineers follow when designing for humans?
- Can you tell me about the design evaluation process from the X-Hab challenge?
    - How do you make sure that the system you're designing is effectively solving the problem it's trying to solve?

    - When did X-Hab/SUITS do the evaluation?
    - What is human-in-the-loop?
    - Is human-in-the-loop a requirement for NASA X-Hab\SUITS?
    - Besides HITL, what other kinds of evaluation methods are you familiar with in terms of system interfaces for humans?
    - What value does HITL have to the overall project?
    - If HITL is tucked onto the end of the project after the system is fully functional, what do you do if you find that the system failure rate is too high?
        - Can you tell me how you incorporated findings from the evaluation into the next iteration?
- Thank you for discussing the X-Hab/SUITS challenge with me. If I may, I'd like for us to pivot now to talk about some other experiences you've had. Can you tell me about any courses you've taken or projects you've worked on where you learned to consider the human user's perspective in the design of a system or software?
    - What kind of content was introduced?
    - Can you tell me what you remember of it?
        - Did you save any of these materials, in Drive or otherwise? And if so, would you be willing to share these with me?

Wrap Up

I think I've asked all the questions I can think of right now. To recap some of the things you've just told me - <summarize key takeaways from the interview for clarity>
Does that sound about right?
Did you notice anything that you would like to clarify?
Is there anything you would like to add that we didn't cover?

Then I just want to thank you so much for talking with me. Learning about your perceptions and experiences with [X-Hab/SUITS] will help me with my research.

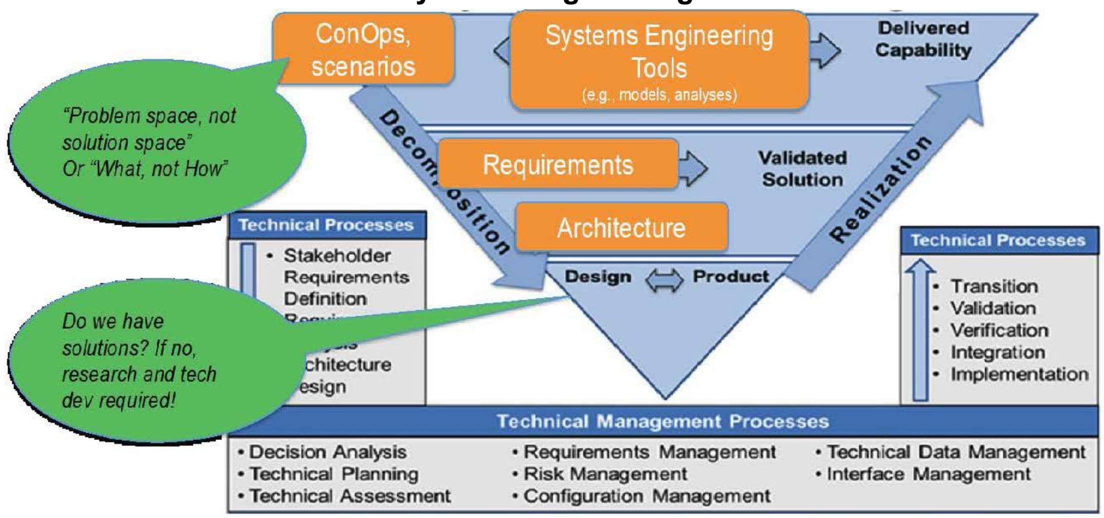
If you think of anything else or have any questions, please don't hesitate to get in touch with me. I'd also like to ask if I can contact you again for a follow-up interview if I think of other questions or need further clarification, is that okay?

APPENDIX C - Keywords for KWIC coding

KWIC Rank	Keywords	Total	AVG	SD
1	Space	180	18.00	12.34
2	System	182	18.20	10.56
3	Engineering	141	14.10	10.00
4	People	146	14.60	9.50
5	User	95	9.50	8.87

6	Design	124	12.40	9.35
7	Team	111	11.10	8.06
8	Astronaut	85	9.44	5.96
9	Test	86	9.56	4.93
10	Requirement	80	8.00	4.85

APPENDIX D - Model-Based Systems Engineering Vee



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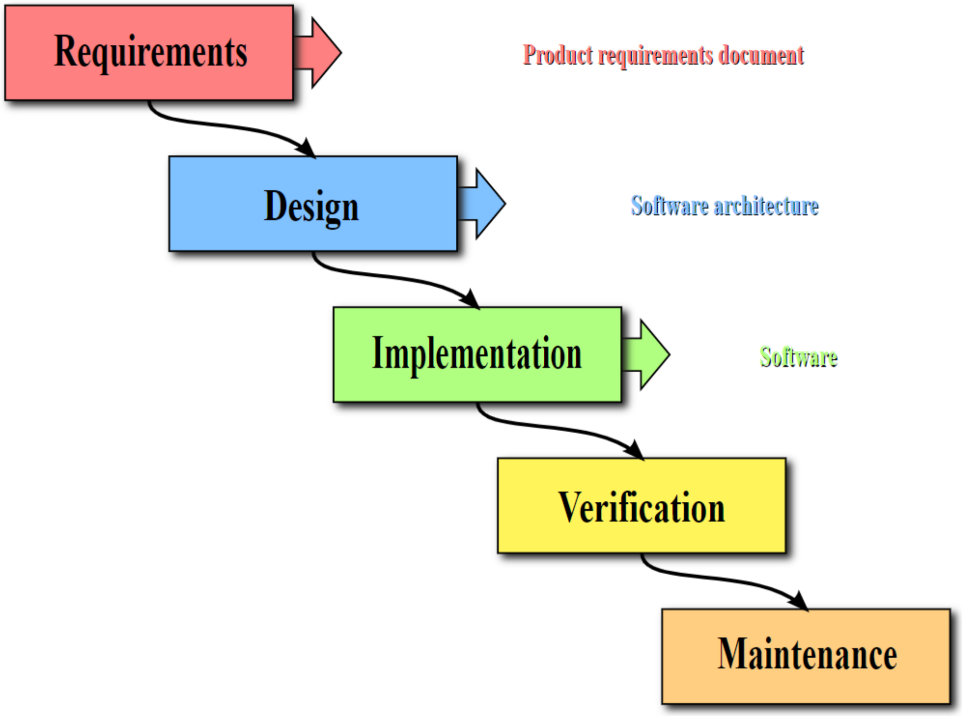
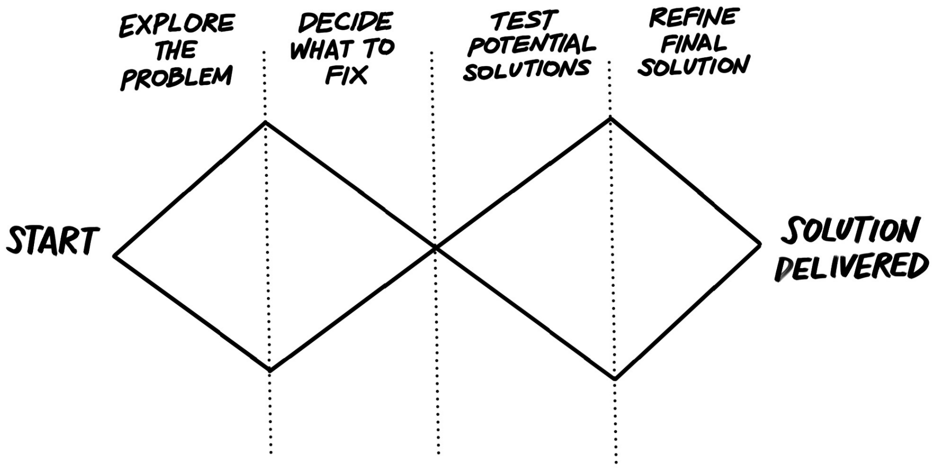
APPENDIX E - Waterfall model



Waterfall model [66]

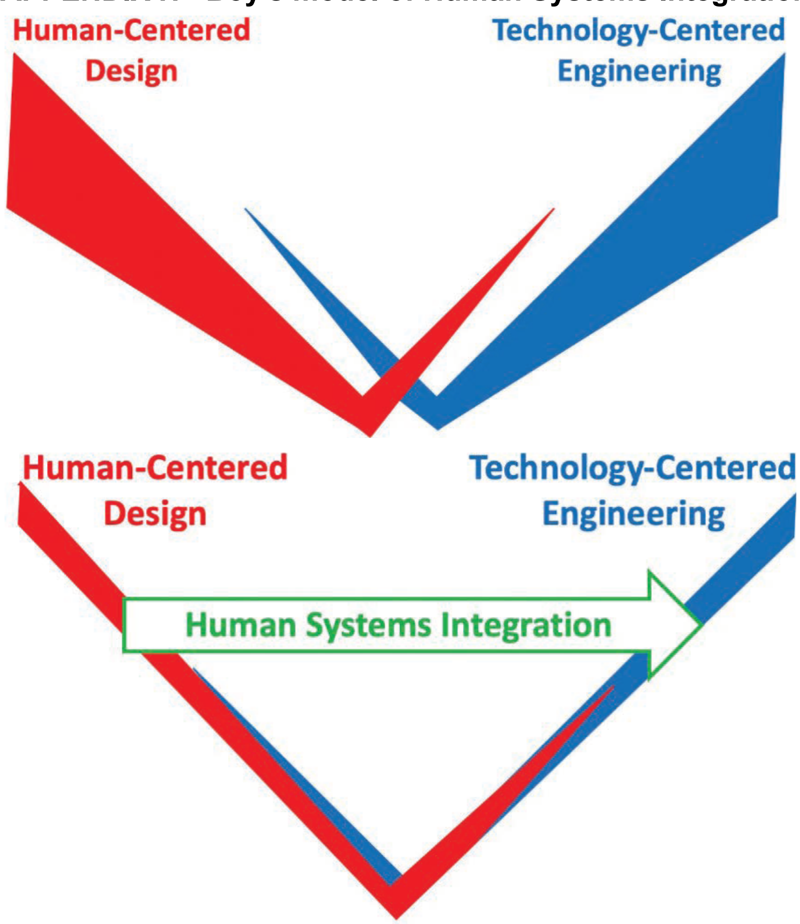
APPENDIX F - Example Design persona

APPENDIX G - Double Diamond Design model



The design council's Double Diamond model [67]

APPENDIX H - Boy's model of Human Systems Integration



Human Systems Integration model [49]