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Team and communication impacts of remote work for complex aerospace system development

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Abstract

Remote work is becoming increasingly common, a trend accelerated by the global COVID-19 pandemic. Existing remote work research fails to address the challenges and needs of engineers working remotely in Complex Aerospace System Development (CASD), the field responsible for creating and operating aerospace systems. This article presents an exploratory study to understand the challenges, benefits, and strategies when working remotely in CASD. We interviewed 12 CASD engineers working remotely at a major aerospace corporation. We ground our findings in six characteristics of CASD work (complex systems; design paths and feedback loops; relationships with suppliers, customers and regulators; distinct knowledge and skills; one-off innovation; and high cost of experimentation) and discuss how each of these characteristics challenges remote work. The findings show that CASD requires many teams to work together, and this is encouraged through informal communication, which almost disappears in a remote setting. CASD requires frequent feedback, and we found that feedback was slow when working remotely. Participants found it challenging to demonstrate systems to customers and verify drawings with suppliers, and the interpersonal relationships, which help to bridge disciplinary divides, were harder to maintain remotely. The one-off nature of the systems designed meant that conceptual work was important, but participants lacked the virtual tools to do this effectively. Lastly, testing hardware components required close virtual communication between technicians and engineers, which was tricky in a detail-oriented context. This study motivates areas for future work to better understand and address the nuances of remote work by engineers in CASD.

KEYWORDS
Aerospace, communication, complex systems development, interviews, remote work, teamwork

1 | INTRODUCTION

Can engineers working on complex systems perform just as well when working remotely as in conventional face-to-face settings? Given that mobile internet, digital tools, knowledge management systems, video conferencing, and cloud computing and storage have enabled new models of work in many industries,[1–3] one would expect increased remote and distributed work by all engineers in the future. However, whereas remote engineering practices have previously been studied,[4] there is a lack of remote work literature specifically for engineers working on complex systems like those in aerospace.

The response to the global COVID-19 pandemic has resulted in restrictions to protect public health.[5] These restrictions have forced practicing engineers to change from co-located work, where they are present in the workplace with their teams, to distributed work, where they work from home, apart from their coworkers. Distributed work from individuals' homes, or simply remote work, is a change that has significantly affected the way work gets done. Popular press examples of teams adapting to this work suggest that engineers have adapted to virtual work with varying success.[6–8] Due to remote work, Engineering organizations face unprecedented challenges to their traditional workflows.

This study defines *remote work* as when individuals in a team or organization conduct work away from their workplace and coworkers, often in their homes. Such a scenario requires individuals to use digital communication tools to perform their tasks and to work with others, sometimes called *computer-mediated communication* in the literature.[9] Other common terms in the literature for remote work are *working from home*, *virtual work*, *geographically dispersed work*, *distributed work*, and *telework*. This study will use the term *co-located work* to describe when individuals are physically together in a workplace.

Particularly challenged by these circumstances are those engineers working on Complex Aerospace System Development (CASD), which is the development and operation of systems in aerospace, such as aircraft and spacecraft. This work is characterized by highly complex, often safety-critical, innovative, and technically challenging projects[10] that require high levels of collaboration, coordination and documentation over a multi-year process. These characteristics make CASD work more challenging to complete remotely. Though international collaboration for global product development is standard for designers to work with suppliers and manufacturers overseas, the predominant working style in CASD remains co-located design teams.[11] In fact, previous research suggests that organizations in an environment of lower, rather than higher complexity, are more likely to adopt remote work arrangements.[12]

Therefore, the global COVID-19 pandemic has created a natural setting to study remote work. This article aims to investigate the gap in remote work literature for engineers in CASD contexts while also providing timely advice for practicing engineers in this area. Thus, the essential research question explored in this study is: *How are engineers working in Complex Aerospace System Development affected by remote work?*

To generate practical insight to support remote work, this exploratory study presents information on the challenges of engineers in CASD, gathered through a qualitative analysis of interviews with 12 engineers. This study will offer insights and solutions that other engineers and their organizations can use to improve working practices within CASD and beyond in remote work scenarios. The study targets experiences and challenges faced during the times when evolving COVID-19 restrictions led to a remote work situation in the region where this study takes place.

SIGNIFICANCE AND PRACTITIONER POINTS

This study reveals that some aspects of Complex Aerospace System Development (CASD) work are feasible in a remote and distributed setting. However, others are challenging and require further research and technology development. For practitioners, this opens up new possibilities for working configurations for CASD teams, particularly a hybrid mix of in-person and remote employees, while highlighting the challenges that we may need to overcome. Whether voluntary or mandated, the study reveals that managers and members of remote teams should be aware of significant strains on communication and relationships, which are critical for tightly coupled CASD work. Given that communication and relationships are not unique to CASD work, managers and team members are encouraged to seek out best practices and recommendations from other fields where remote work has been practiced in the past. In particular, managers should anticipate challenges with cross-team informal communication, getting feedback quickly, displaying systems to customers, maintaining relationships, doing conceptual work, and testing hardware components. In general, CASD worker attitudes are positive towards at least some element of remote work for themselves in the future, and thus managers who adjust their workflows to accommodate such interest might anticipate advantages in attracting and retaining employees.

For fellow researchers, our exploratory results reveal several questions and topics that warrant deeper study: virtual methods to view and inspect hardware for design, manufacturing quality control, and formal design reviews; communication platforms that support remote CASD work and how large organizations can adopt them; and how to achieve the benefits of informal communication in remote and hybrid teams. Considering the endemic nature of COVID-19, and the world's shift to remote work, we expect that these configurations will keep hold at CASD organizations to some extent. Our study's scope is one organization; therefore, studies that expand and test the generalizability of these findings would undoubtedly expand the frontier of Systems Engineering knowledge.

When investigating new and unstudied phenomena, Szajnfarber and Gralla recommend that qualitative researchers ask, "What is this an instance of?" to guide their literature review and to establish a research question.[13] For this study, the context is an instance of three domains: remote work, Aerospace Engineering, and complex

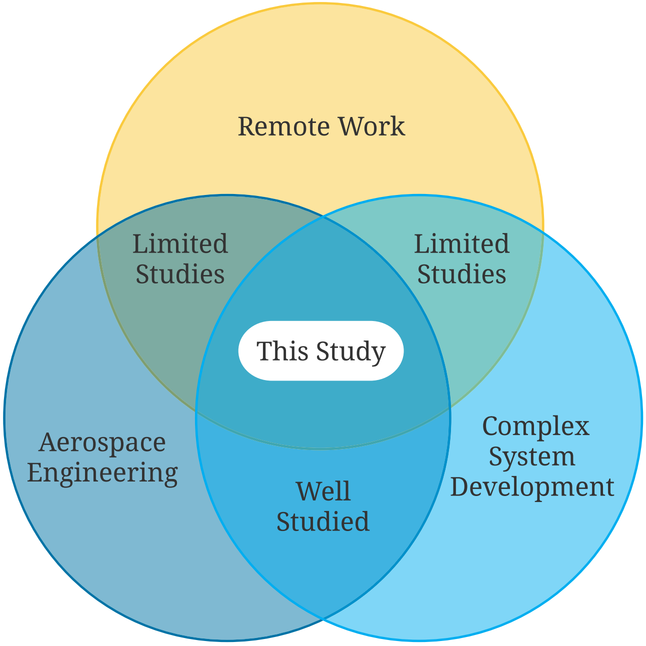

FIGURE 1 Position of this study within existing research.

system development, which is closely related to Systems Engineering (SE). All three of these domains are individually well-studied. The intersection between Aerospace Engineering and complex system development is also a well-studied area due to the complex nature of modern aerospace systems. However, both Aerospace Engineering and complex systems development have not been addressed from a remote work perspective. Further, all three have never been combined. Figure 1 summarizes the scope of this study.

Thus, we contribute the first study of remote Complex Aerospace System Development and provide an initial framework describing how the characteristics of this type of work impact the possibility of flexible working schedules. We provide practical implications for current CASD managers and their teams as they decide what the future of work will look like, and identify rich areas for further theoretical work.

The rest of this article is structured as follows: first is the background section describing key concepts and highlighting past relevant work; next, the interview method is described; the results section contains findings from the interviews; the discussion section places these findings in the context of past work and existing theories, and; finally, this article concludes and discusses directions for future work.

2 | BACKGROUND

Remote work is well studied, and research has been compiled into literature reviews for over 2 decades.[14] A recent literature review on the topic published in mid-2020 by Morrison-Smith and Ruiz[9] provides a comprehensive benchmark on the current state of research in this area. Of the variety of research contexts in this literature review, none specifically target engineering outside of Software Engineering, and Software Engineering studies comprise only a small fraction of the total studies.[9] Further, all works compiled predate 2020 and thus do not consider the unique challenges of remote work during the COVID-19 pandemic. Instead, the literature review states that remote work is motivated by the forces of globalization,[9] a very different driver than the COVID-19 pandemic.

Though not well captured by the Morrison-Smith and Ruiz[9] review, remote work has been studied in the general engineering context,[4] and more specifically, for SE.[15] SE is highly relevant to the present study because it is a discipline employed heavily in complex system development. SE is a socio-technical activity of human problem-solving and thus requires teams to cooperate closely. It follows that the SE community's opinion is that co-located work is better than remote work because of the facilitated collaboration.[15] More than 20 years ago, Harris[15] identified that the SE community should evaluate their remote experiences and determine their communication needs.[15] This research area has not been addressed, and this gap is highly relevant due to COVID-19.

In contrast to the remote work research to date, the present study will consider the context of the COVID-19 pandemic and its role in the remote work practices we see today. Remote work during COVID-19 differs in several ways: First, it is involuntary, meaning it occurs regardless of individual preferences. Second, its onset was unplanned, and the future of remote work is unclear. Third, it fluctuates such that individuals may return to their place of work occasionally, subject to varying public health orders in the region. These characteristics are discussed when they apply to our findings.

This study will elucidate the nuances of what individuals face when working remotely in CASD and connect these experiences with the literature. The article includes a discussion of so-called "soft" aspects of CASD, a generally under-studied lens in the field of design.[16] Remote work is a broad concept, so this study has been scoped to a few key topics. First, the context of CASD is important, so we focus on key aspects that define CASD. We also focus on communication, as this is critical to SE and is shown to be impacted by remote work practices. Lastly, we touch on trust and shared understanding, which are concepts important both for remote work and complex systems development.

2.1 | Complex aerospace system development

CASD is a type of work in which complex aerospace systems, a specific form of a complex product or system (CoPS), are developed. CoPS are defined as high-cost, customized, and complex, and are contrasted with low-cost commodity goods, which are mass-produced and based on standardized components.[17–19] Hobday argues that designing these CoPS, which have different product and production characteristics, also have different innovation processes, competitive strategies, industrial coordination, and market characteristics. In his seminal paper, he describes CoPS and discusses eight critical dimensions of these products: complexity, product architectures, design paths and feedback loops, breadth of knowledge and skills, coordination across units (customers, suppliers, and regulators), embedded software, product profiles, and implications for experimentation. We conjecture that these features of CASD impact the ability of these designers to work remotely, and thus these features will provide context for some of the challenges they are experiencing.

Further background on the context of CASD work and its reliance on co-location is also relevant to this study. These aspects are covered in the following sections on design phases; and, hardware and assembly, integration, and test (AIT).

2.1.1 | Design phases

The NASA Systems Engineering Handbook[20] provides a widely adopted framework for the phases and milestones in projects undertaken in CASD. We chose this process model for the study because of its ubiquity in Aerospace and Systems Engineering. The handbook breaks a project into seven life cycle phases, designated Pre-Phase A, Phase A, through Phase F. Phases A and B occur early in the project before any significant fabrication of components or detailed design occurs. Phase C is the period for detailed design and the start of fabrication. Phase D is where the overall system is fabricated, integrated, tested, and finally completed. In the context of this study and many CASD programs, the result of Phase D is the construction of just one final device or vehicle (often called one-off innovation). Multiple copies may be produced, but there is no mass manufacturing. Phase E is the operations phase which occurs after the project has been successfully developed and put into flight operations. Phase F is when the system is taken out of operation. In summary, the authors would expect that the effect of remote work on a CASD team would depend on the phase in which that team works, and we investigate this in our study.

2.1.2 | Hardware and AIT

AIT collectively refers to Phases C and D tasks and consists of the final work done on the project before completion and operation. The development of complex systems involves an extensive set of tests,[21] and these tests place different requirements on the project members to interact with hardware. Assembly requires extensive interaction with the hardware, whereas integration and testing could be accomplished through simulations or remote access to hardware components, though this varies case-by-case. For the context of this study, it is well established that numerous aspects of AIT require the co-located use of facilities, equipment, and hardware, some of which are very specialized.[22],[23] With the co-located requirements of AIT, the constraint of even partial remote work will create challenges in this aspect of projects.

2.2 | Communication

Morrison-Smith and Ruiz[9] captured that work can be categorized as "tightly coupled" or "loosely coupled." Tightly coupled work is characterized by being non-routine, complex, and reliant on the individual's skill. Tightly coupled work requires rich communication due to its complex nature. In a remote work scenario, tightly coupled work encounters challenges due to strained communication, resulting in mistakes and less successful projects.[9]

Tightly coupled work matches the work expected in the complex systems development work investigated in this study. This similarity, therefore, predicts the importance of communication in our context. Specifically, many studies have found that in tightly coupled work, the structure of the product or system being designed mimics the organization's communication structure, or vice versa, and this mirroring results in improved performance.[24] However, literature also shows that communication changes when working remotely.[9] This finding motivates an investigation of communication in our teams and a comparison of findings with the literature.

Communication is one of the fundamental challenges in remote work for engineers. Engineers, including those in aerospace, spend more than 50% of their working time communicating, and that is increasing over time.[25] Further, communication becomes more complicated for engineers working on more complex technical systems, such as those investigated in this study. Lastly, the learning style of engineers emphasizes listening and discussing over reading.[25]

Any impact on communication during the remote work period will thus present challenges to engineers. A loss of informal communication, the extra effort required to communicate remotely, strained managerial responsibilities, and personal levels of digital technology confidence are all ways remote work may negatively impact individuals' communication compared to co-located work.[9,26]

Communication between engineers occurs in different ways, which can be described as channels. Communication channels include informal discussions, internal presentations, or written communication, such as emails. Similarly, findings from surveys of engineers state that the frequency of use of a communication channel does not depend on the intrinsic value of the channel, but instead on the accessibility of the channel.[25] This insight indicates engineers prefer easily accessible, informal, and oral communication channels. An example of a communication channel for collaboration is the whiteboard, for which researchers identified the importance of establishing an online equivalent for over 20 years ago.[27]

An important type of communication for engineers is informal communication. Engineers, including those in aerospace, favor oral and informal communication and have been found to spend nearly 10% of their working time on informal communication alone.[25] Morrison Smith and Ruiz[9] explicitly identify an open research gap for better supporting informal communication.[9] In response to this question and the literature presented thus far, this study explores informal communication and communication channels in a remote work scenario for engineers in CASD.

2.3 Trust, awareness and shared understanding

The tightly coupled nature of complex system development work naturally benefits from informal communication between engineers, which results from established interpersonal relationships. Trust, awareness, and shared understanding are key factors that impact these aspects of interpersonal relationships and informal communication.

Trust is one of the most studied aspects in the literature on remote work, and it remains a popular topic.[28] Prior studies show that remote collaboration benefits from having the individuals involved share a "common ground" from working together before and sharing experiences. A lack of common ground leads to difficulties building trust and communication in remote work,[9] also known as the mutual knowledge problem.[29] Trust is crucial for remote teams, but many barriers exist to building trust in remote settings. These include the difficulty in conveying nonverbal cues using video calling tools or any other platform, the reduced frequency of interactions, and the lack of face-to-face time to build initial trust in relationships between coworkers.[9]

The extent to which relationships are established also changes the communication needs of a team during remote work. More experienced teams need less synchronous technology to accomplish their task, whereas teams in the early stages benefit the most from synchronous options like video conferencing.[9]

Another dimension of teamwork is *awareness*, which is a well-explored concept defined loosely as the sense of presence of others in one's work environment.[9] It is well established that compared to co-located work, awareness is reduced during remote work. Past studies suggest the cause of this is simply that remote workers have fewer opportunities for casual encounters and spontaneous conversations characteristic of informal communication.[9] In this sense, the overlap in awareness of the goals, tasks, processes, team interactions, and information about team members is defined as *shared understanding* within a team.[30] The loss of awareness, or a lack of shared understanding in remote work, is problematic because it is linked to several benefits. First, it provides context for employees' activity, ensuring that individual work contributions are compatible with the group's collective activity. In the tightly coupled work of CASD, this is particularly critical.[9]

Second, it is tied to individual motivation to work effectively. That is, people tend to work harder when not alone.[9] Remote work during COVID-19 has the potential to be particularly isolating for employees, and feelings of isolation reduce contributions and participation in teams.[9] Third, the inability to observe others' efforts during remote work leads to perceptions of others' efforts that can be overly negative. Such negative perceptions could damage relationships between team members, impacting the highly collaborative work of CASD. In summary, the established importance of trust, awareness, and shared understanding in remote work literature motivates exploring these concepts for similar problems and may also permit strategies presented in the existing literature to be applied.

3 METHODS

3.1 Research context

We used interviews to gather the remote work experiences of our participants. Qualitative research originates from the social sciences,[31] yet it is beneficial for research in engineering,[13] especially in exploratory contexts. Using the standards outlined by Szajnfarber and Gralla,[13] a qualitative approach is well suited to this study's goals because of the lack of literature tailored to the remote work practices of engineers in CASD. Further, a qualitative approach is the best way to make sense of the human and contextual drivers at the intersection of remote work and CASD by permitting a deep exploration to uncover insights not captured in existing hypotheses or theories.

The interviews were semi-structured, conducted with one participant at a time, lasting at least 1 hour, and conducted via Whereby,[32] a video conferencing software. Interviews were guided by a predetermined set of questions, which we deviated from where appropriate. The interviews covered the following topics: their background at the company, projects they work on, and prior remote work experience; the challenges they face and how these relate to CASD; how specific design phases or activities (including AIT) have been impacted; how they use artefacts and whether this has changed; and any tools they use when working remotely. The interview sample included 12 participants at a single Aerospace Engineering company. Ten of the 12 participants were chosen based on the recommendation from their department manager at the company. We requested that the department manager try to vary seniority, gender, and experience with prior remote work when recommending individuals. Participants were only recommended to the researchers if they were interested in the study, which was determined prior to being contacted by the researchers. The remaining two participants were selected based on the suggestion of one of the other 10 participants. These two participants were suggested because they work in mechanical design, which became a more prominent focus of the investigation as it was discussed extensively in the second interview. Note that the study was approved by the University of Toronto Ethics Review Office.

The interview questions were relayed to participants in advance per the department manager's request to ensure no questions would lead participants to reveal sensitive information or company intellectual property. We also provided unedited transcriptions of the interviews to the company for review, so redactions of sensitive information could occur if needed. In the review of the proposed questions, no changes were required. In the review of the interview transcripts, only three required redactions and changes were made, and these were minor and not directly related to the topics explored in this study.

The participants continuously experienced remote work for 7 months before the start of the interviews. Interviews were then conducted over another 4 months consisting, largely but not entirely, of remote work for participants. During both these periods, the total number of employees at the organization working remotely was estimated to be between 80% and 95%. Therefore, the extent of remote work at this company impacted all employees. The company had never experienced a remote work situation of this nature before. The significant duration of remote work prior to data collection means participants and their company had the opportunity to adapt routines and work processes or develop new ones. This timing positions this study to focus on the steady and medium-term considerations of remote work, not the sudden transition process from co-located to remote work.

3.2 | Thematic analysis of transcripts

We analyzed the reviewed interview transcripts using the qualitative research software NVivo.[33] The second author completed the analysis using the Braun and Clarke thematic analysis method.[34] We began by open coding the transcripts, which consisted of identifying statements made by participants and coding the relevant topic represented in that quote. The unit of analysis was, at minimum, a sentence, but often consisted of a paragraph. Previous interviews were revisited when new codes emerged. The codes from the open coding process were then grouped and organized hierarchically to expose the core themes. Two authors then iterated upon the organization of codes into themes to answer researcher queries and interpret results. At this point, we returned to past work, described in the background section, and iterated between the themes and literature to draw meaning from the data.[35]

The analysis aimed to determine trends and discrepancies between participants and identify the driving forces behind these differences. The analysis also intended to seek themes core to all participant experiences. During the process, some thematic areas were removed from the study scope to ensure those with the most valuable results could be presented in rich detail. To this end, results in this study are formatted as thick descriptions to provide full details on the experiences captured, similar to other studies using these methods (see literature[36–38]).

3.3 | Participant demographics

Of the 12 participants, there are eight men and four women. The participants' age distribution is as follows: two are between 20–29 years old, six are 30–39 years old, two are 40–49 years old, and two are over 50.

We identified all participants as engineers based on the type of work that they do and the departments they work in. Participants came from various engineering backgrounds, such as Mechanical, Electrical, and Aerospace. The authors assert results of this study remain applicable to engineering broadly. Preliminary findings based on interviews with six participants that focused exclusively on Systems Engineering are available for reference.[39]

We interviewed eight employees with the title senior engineers, one with the title engineer, one with the title intermediate engineer, and two junior engineers. Three senior engineers and one intermediate engineer participants manage others as part of their role.

4 | RESULTS

In this section, we present the results from the thematic analysis of our interviews. This section is presented around the characteristics of CASD, discussing how various characteristics of this specific type of work make remote work challenging. In the following section, we bridge these individual findings to engineering theories to highlight flexible work's implications on CASD processes and products.

4.1 | Characteristics of CoPS

As described, CASD is a type of work which fits into the CoPS category from Hobday, which are high-cost, customized, and complex products and systems, as opposed to commodity goods.[17] We argue that these characteristics challenge remote work practices in new ways, and we organize our results around this framework. We adapt this framework slightly to represent complex systems in modern times. For example, we combine product architectures (the idea that CoPS have multiple possible product architectures) with complexity, as characteristics of the product architectures are cited as one possible measure of complexity.[40] Further, we do not specifically discuss the impact of embedded software as this is now common in many products[41] and no longer distinguishes CoPS. Our adapted version of this framework and our findings within each characteristic are shown in Figure 2.

Though we note that many of the participants did not believe their challenges to be unique to work in CASD, we use this framework of CoPS work to discuss how the challenges participants experienced may have resulted from, or be exaggerated by, the characteristics of the work participants were completing. Participants stated they would expect their remote work experiences to apply to similar lines of knowledge-based work. The one exception is the specific kinds of testing done on aerospace equipment. This finding suggests that we may be able to turn to existing literature studying remote knowledge work to contextualize our findings within CASD.

4.1.1 | Complex products and systems

Hobday[17] describes CoPS goods as complex, where complexity can be defined by the architecture of the product or system, the number of subsystems, the degree of customization, or the degree of technical novelty. Hobday describes how CoPS have multiple potential architectures, which in our adaption of this framework, we consider another measure of complexity. The complex nature of the aerospace systems developed by our participants challenged their ability to work remotely

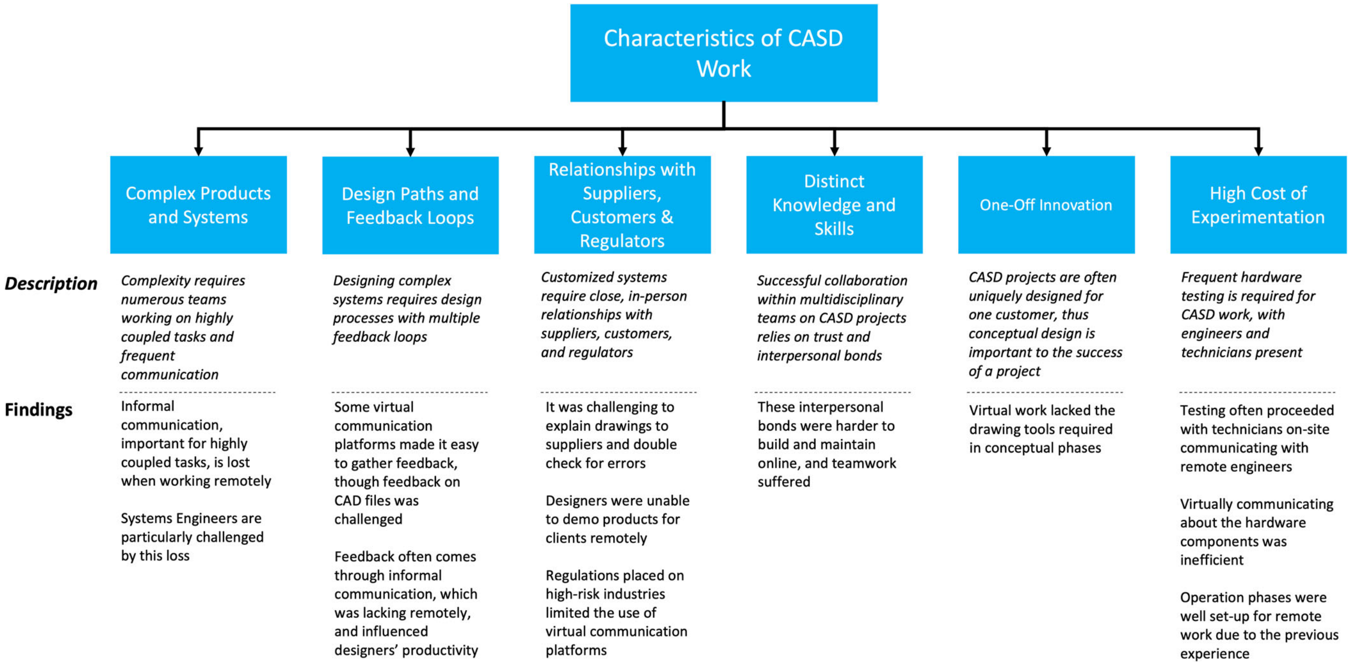

FIGURE 2 Results of our study described within the framework of complex products and systems from Hobday,[17] with minor adaptions.

in several ways. Designing complex systems requires diverse skills, and each subsystem is often designed by its own team. The work that these diverse teams do is highly coupled, meaning that one team relies on the work of another. These characteristics of complex work mean that many diverse teams must closely collaborate in designing and implementing these systems, and communication, particularly informal or unplanned communication, is critical for this continuous adjustment.[9] Informal communication is crucial to the role of Systems Engineers as they integrate components and subsystems of the final design. We observe that the Systems Engineers at this organization were particularly challenged when working remotely due to the lack of informal communication.

Interviews with participants revealed extensive communication challenges during remote work and the produced strategies to adapt and succeed. These emergent challenges and strategies demonstrate the core role communication plays in the engineering work in CASD due to its tightly coupled nature. As one participant summarized, "*if you don't keep in communication with everybody and you don't streamline everything, then it's a big chaotic mess.*"

Much of this communication between tightly coupled teams used to happen informally, such as at the edge of meetings, in the hallways, or in the lunchroom, often referred to as 'watercooler' conversations.[42] Informal communication is spontaneous, unplanned, and is described as chance conversations that arise typically from co-location in the same space. Informal communication can also be intentional, like visiting someone's desk for a quick question. The *informal* aspect does not imply it is not work-related, just that the communication is not scheduled on a calendar like a meeting.

In the absence of these opportunities, participants described that building and maintaining relationships was challenging, which harmed the flow of information to support tightly coupled work. A senior engineer participant succinctly expressed that "*it all comes down to information transfer and how you basically communicate with other human beings. […] If you don't have that flow of information, it's very hard sometimes to do your job.*"

This flow of information due to informal communication was found to have several implications. First, it provides individuals with improved awareness of what is happening on other teams and opportunities to do work outside their typical scope. One participant said, "*you can kind of expand your own knowledge that way.*" Second, newly hired employees miss out on gaining tacit knowledge of the company normally acquired through informal conversation while co-located. We heard that the lack of tacit knowledge extends beyond immediate onboarding and may impact new employees several years after being hired.

One strategy that participants suggested to overcome the lack of informal communication when working remotely is to organize work differently. They offer "*a key area for adapting to [working from home] is work organization—clear chunks allocated to [individuals], [as opposed to in-office work] where more loosely defined tasks and higher frequency interaction could normally be employed.*" However, it is unclear to what extent such complex work could be decoupled.

Findings on replacing informal communication in remote work were limited. The random and often unplanned nature of informal communication makes it both valuable and difficult to reproduce remotely. Prior remote work was occasionally motivated by a desire to avoid informal communication, which presents a strong statement that remote work is not perceived as promoting this kind of communication. Participants expressed discomfort in starting virtual conversations with others they haven't met. Also, there are mixed opinions on whether the available messaging platforms (Slack and Zoom) are suitable substitutes. The main area of praise and criticism towards these platforms centers on time, "*I do like the Zoom messages. I like how quick it is. I like how I don't have to write up a formal email. I can just shoot a quick message and get a quick response. It seems pretty comparable in some ways to going by their desk with less overall chatter…but I have heard other people complaining and they don't like getting too many Zoom messages*." Participants like how quick the instant messaging platform can be, but sometimes waiting for a response may take as long as booking a block of time in advance.

Communication matters for all engineering disciplines in CASD, but the extent varies. One of the Systems Engineers interviewed exemplified this best, describing their roles as being the "glue" of a team that relies on communication, *"I think of Systems Engineers as kind of like the glue that holds the team together, right? You really have to be in constant communication with everyone on your team, all the different groups, making sure that the interfaces are going to come together properly, that it's not just those sub-disciplines designing and working in isolation of each other. And that all that meets what your customer needs in the end."* A shift to remote work has had a particularly large impact on the Systems Engineering discipline because of the changes in communication for this tightly coupled work. Another senior Systems Engineer participant stated, *"I have found over the years that it is 10 times more effective to go and sit at someone's desk, actually probably closer to a hundred times more effective, than to fire an email off into the ether and which they're very busy, they don't see it, or even phone calls and they go unheeded and stuff like that."*

Exacerbating the communication challenges experienced when working remotely is the disparity of adoption of communication platforms between teams and departments. One participant explained that, with communication platforms like Zoom, *"everyone has to buy into it"* to make it work effectively; otherwise, the benefits are lost. The disparity of adoption observed is evident in the extent to which new communication platforms are used.

A participant described different "*camps*" of communication platforms within the company, in this case, the "*Zoom camp*" and the "*Slack camp*." Zoom is a video conferencing software,[43] and Slack is an organized instant messaging platform where participants can send messages between individuals or in channels with several individuals.[44] The tension is over which platform to use for text-based instant messaging. A participant who spoke for the employees who prefer Zoom for instant messaging said, "*we had Slack channels before where we could message each other, but Zoom is a much easier interface.*" Others supported using Slack, stating, *"even if I'm in the building, we would use Slack to communicate. […] Way more effective than texting cause everyone kind of knows what's up. And so that's kind of trumped any email. […] The day-to-day activities, they're all kind of coordinated through Slack."*

The individual preference for platforms varies by role and team. These preferences lead to challenges in communication between teams who use different platforms. The result is added frustration and awkwardness when trying to communicate and extra work for employees to track others' preferences: "*like in my role, I have to kind of be able to get a hold of everybody. So I have all of them, I have all the Slack and all the Zoom and all of it*."

A likely driver for this disparity is a lack of clear organization-level standards for using communication platforms because of the rapid shift to remote work.

In summary, the complex nature of CASD work requires collaboration between many teams, and we found that this collaboration relies on the informal communication that often happens in the office. Without this, it is harder to complete tightly coupled work, which most impacts Systems Engineers. Further, our participants shared that it was essential for all teams who interact to use one virtual communication platform.

4.1.2 | Design paths and feedback loops

Another characteristic of CoPS work is the many design paths, or processes, that could be followed and the feedback loops within phases of these processes.[17] Designers consistently provide feedback on designs and iterate throughout these systems' development. Often, they need to provide feedback on hardware components, materials, or 3D Computer-Aided Design (CAD) models. It is essential to study this process because, as one participant said, "*How we do what we do is as relevant from a process perspective as the work itself, and often something that is given less attention than is warranted*."

We found that this iterative design process influenced remote work in two ways: first, some new virtual communication tools made it easier to reach team members for feedback, though feedback on CAD models was challenged when communicating remotely. Second, while some participants could provide and receive feedback using virtual communication tools, others felt strongly that this component of CASD work required the previously defined informal communication that existed in the office, and that feedback was slowed, and thus they were less productive, without this.

Some of our participants said that the new communication platforms, such as Zoom and Slack, helped gather feedback from coworkers, and they would like to continue using these platforms even when returning to co-located work. The Zoom platform is one example: *"Zoom is nice in that I can communicate to several people without needing to go find a room or get a projector. I can annotate, and everyone can annotate on the screen at will, and keeping track of it all is as simple as pressing the screen capture button."*

As a specific example of using Zoom to provide feedback, three participants from this study belong to the same team, which was geographically distributed between two in-person offices before the remote work period. This specific team will be referred to as Team A through this study. Before the remote work period, to support operations, Team A would provide *"active support,"* watching live operations activities to enable them to call experts immediately in response to problems. Since the onset of COVID-19 remote work, this team has used Zoom to create a virtual *"backroom"* with the relevant experts all present and watching. The presence of experts in this backroom streamlines the process of getting input for Team A, letting them provide faster overall support than the previous method.

After the first time doing this, the team decided they "*should do that more often.*"

This strategy was not used before because Team A *"didn't really have a tool"* because they *"didn't really know about Zoom."* This example is unique in this study's findings, likely because this team was previously geographically dispersed. The forced shift to remote work for the whole organization presented Team A with new connectivity technology to improve their processes.

Another example that has more adoption at the company is the messaging platform Slack. The platform's channel-based messaging functionality could have mitigated the problems described by one senior participant in an experience before remote work, *"I was part of a design review. […] They had a deadline they were trying to meet. And so […] as a 12 to 16-person team, we had to review three major subsystems in 5 days, and we did it entirely through email. And it was the worst experience of my career at [the company]."* The communication tools adopted to address the forced remote work seemed to be an upgrade from the prior tools.

However, not always were virtual communication tools conducive to providing feedback. For example, participants shared that CAD model communication is difficult on a distributed team. Previously, individuals were co-located in a room where they could collaboratively view and discuss models. However, now they must annotate PDF files or images, sharing these over email or screen sharing on a video call. Participants described these methods as time-consuming: *"The biggest change for me is the amount of time I spend communicating design and modelling updates to non-CAD users."*

Lastly, participants described how much of the feedback they received happened during the informal 'watercooler' communication in the office. They described a strong connection between informal communication, feedback, and productivity—the rate at which formal work output occurs. During remote work, participants reported it takes longer to get in touch with people when needing feedback without desk chatter, as booking calls are a burden. Further, some participants feel using messaging platforms is not as easy as walking over and talking while co-located, "*if I was in a position where I needed to get in touch with people, it takes longer. Now, I have to set up a meeting…what might be a 5 min conversation turns into a 30-min conversation, potentially cause I don't go to their desk. Now, I have to book a time with them.*" This challenge was also noted in studies of physical product designers, where iteration is also common in the design process.[42,45]

Further regarding feedback, participants described that having co-located desk arrangements was conducive to improving productivity through communication before the remote work period. One participant intentionally situated their desk with other engineers organizing the same project, enabling them to overhear conversation easily. Another participant went a step further to leverage the full benefit of co-location to support feedback on hardware work: *"I moved my entire computer out to the shop floor, right beside the hardware. I was working on a completely different program's work, but every once in a while, the technician would say, 'Hey, this doesn't look right.'[…] And just being there beside them, they ask a really quick question that they probably wouldn't have asked if I wasn't there."*

In summary, the frequent feedback needed by CASD engineers may be made easier by some of the newly implemented communication tools, though some of the complex feedback regarding CAD models is still challenging. Further, participants once again emphasize the importance of informal communication in their day-to-day work; they describe how this was often one of the ways they received feedback on designs, and without this, feedback was slowed, and thus they were less productive.

4.1.3 | Relationships with suppliers, customers and regulators

Hobday differentiates CoPS from mass-produced commercial goods due to the required close relationship with suppliers, customers, and regulators.[17] Since CoPS are often one-off products, designed uniquely for one customer, the customer is highly involved in the design process, usually present at testing and providing approval at multiple stages.[17] Suppliers are often heavily engaged in the CoPS design process, as designers may need to order custom parts. Additionally, because CoPS organizations often operate in high-risk industries, such as the aerospace organization we study here, they are highly regulated. Here, we show how these necessary relationships with suppliers, customers, and regulators challenge the organization's ability to work remotely.

Participants described how remote work made it more challenging to communicate with suppliers, which represents a supply chain concern for procuring parts. It is generally less convenient for suppliers to ask questions that could have led to error correction, "*they made a choice without consulting me, and it had a fairly dramatic impact to the overall build.*" Several participants highlighted that explaining mechanical drawings on-site with a supplier is important because of the many possible interpretations. It is difficult to communicate physical features, even with drawings and CAD. During the remote work period, it was impossible to visit the suppliers producing the hardware to explain or perform the inspections before the final shipment to "*make sure they're interpreting a drawing correctly."* These visits were previously done because communicating about physical hardware, CAD, and drawings was expressed as extremely difficult or impossible when done over a video call.

Due to this limitation, the company had to change the quality clause in their contracts and resorted to using photos of the hardware for inspection. However, photos were not as effective as an in-person inspection, and as a result, there have been *"big glaring errors that would not have made it through the chain if we were allowed to be on-site and inspect properly."*

Participants also described challenges in demonstrating hardware, mainly functioning electro-mechanical systems, to customers. In the past, customers could visit the company site to inspect hardware and watch a live demonstration. The hardware's scale, detail, and subtle motion make it difficult to use traditional video calling software to provide a demonstration. One participant describes: "*So instead of [the national agency] getting to see hardware performing in its demos, they're watching the Zoom videos and a couple of the folks on the [national agency] side, they had latency issues there, their internet wasn't the best. And so the impression that the hardware gives is diminished when the reviewer is annoyed at the technology that they have to view that through.*" Participants described trying to improve the technology used, to some success, "*we set up this HD camera and did a live video feed through Zoom in HD. Cause they want to look at like this little mark over here.…I'm talking like tiny, tiny, tiny, like I'm zooming in on this HD camera. Like, can we see it now?…but we did make that happen. So that was a way to get around some things we just can't change.*"

Lastly, our participants did not share any challenges related to their relationship with regulators, though they did discuss how the regulations placed on them limited their ability to adopt traditional virtual communication tools. For example, a significant limitation of Slack at aerospace companies like the one studied is that documents, data, and sensitive communication must still be sent via email to follow the regulations on data security. One participant shared, "*we don't hold the servers for those Slack channels. And so I can't communicate program info or sensitive info through Slack, and that makes it almost useless for me. I use Slack to keep track of my board game meetings group…it's just a side tool for communicating socially.*" The need for secure file transfer is somewhat unique to aerospace projects and creates an additional challenge to overcome with remote work.

In summary, close relationships with suppliers and regulators are critical to the success of CASD projects. However, these relationships rely heavily on viewing physical documents and hardware, which is challenging during remote work, with no good solution yet. Further, the regulations placed on CASD work limit the virtual tools they can adopt to help overcome these challenges.

4.1.4 | Distinct knowledge and skills

Another characteristic of CoPS work is the distinct knowledge and skills required to design complex products and systems. For example, in the organization studied here, teams consist of Mechanical, Electrical, Aerospace, and Systems Engineers, all with specific roles in the design team. This diversity means that experts with different backgrounds, who may "speak different languages," must collaborate closely to decide on the system's design. In these multidisciplinary design team collaborations, a recent review showed that trust was critical to positive design outcomes,[46] and one way that this trust is built is through interpersonal interactions,[47] which facilitates the discovery of others' perspectives. Thus, interpersonal relationships and teamwork are critical to bridge different expert knowledge in multidisciplinary CoPS teams, and we found that the ability to build these relationships was challenged when working remotely. In this section, we use the word *teamwork* to describe what it means for people to work together, build relationships, and function as a team or organization.

All participants reported negative impacts of remote work on teamwork. Two participants captured this well, the first stating, "*I'm a huge fan of people participation on teams, and to do that, you need to build team spirit. You need to have people in the same room eating cookies. It's very hard to do that remotely.*" And the second explains, "*the key is the synergy with the customers, the [in] person time with the team to make sure there's an understanding of what each [team member] is able to do. They understand who to talk to, when to talk to them. And there's a good rapport, right? So that's critical.*"

The driver of this negative trend is the loss of opportunities for socialization and interpersonal bonding activities. Participants did describe the efforts being made to create these opportunities, such as virtual "*lunchtime sessions*," but it was not consistent between participants and did not occur as often as they desired. Participants also reported missing their colleagues and expressed that existing relationships with others outside their team had broken down during the remote work period. Examples of this are no longer having the opportunity to speak with a desk neighbor and a lack of social drinking with coworkers. Compounding this problem is the trend that at "*almost all meetings, everyone has cameras off*" while on video calls. Building relationships and team rapport is difficult when employees cannot see one another.

Another teamwork trend relates to onboarding and the experience of recently hired employees. The training and integration of new and recently hired employees was brought up as a particular problem by participants who were both recently hired employees and those in the position of onboarding others. Other work investigating the impact of remote work has come to similar conclusions and attributed this to a lack of mentoring when working remotely.[48] This topic was frequently mentioned in interviews because of the large amount of hiring during this study. These new employees may struggle to receive feedback on their performance due to cameras being off in video calls. One junior participant expressed, *"so trying to figure out how I'm performing […] when I can't see their facial expressions […] it's felt a little bit trickier to just kind of know where I'm at and how I'm doing. Unless if they're actively verbalizing it and giving me feedback regularly."* Feedback on performance must be actively sought or provided instead of given implicitly. Our participants also explained that it is difficult for existing employees to reach out and develop relationships with new hires. Unprompted communication during remote work was described as awkward, and there were few social venues to meet new employees. Participants notably identified that more co-located time would help build relationships with new and recently hired employees. A possible solution to this problem is to encourage existing employees to reach out to new and recently hired employees and create explicit opportunities for this, such as through virtual watercoolers.[49]

There are comparatively few instances of improved teamwork due to remote work reported by the participants. The best example again comes from Team A. Participants on Team A described improved team dynamics and stronger relationships with one another after the start of the remote work period. One member of Team A stated, *"I think all of us sort of tend to agree that this has been actually a good thing for the team, weirdly."* Improved team dynamics and stronger relationships appear to be driven by the increased use of Slack and Zoom platforms between team members. Team-wide adoption of these platforms seems to have created a low-friction way to interact and build interpersonal relationships, aligning with the research which suggests that ease of use is a driving factor for adopting communication platforms.[25] Further, members of this team seem to have more time to focus on relationships with one another, as connections with others outside their team had broken down after no longer being co-located.

Another finding identified is that individuals who work with those with whom they have a pre-existing relationship have positive teamwork experiences during remote work. These pre-existing relationships result from working with others on the same or previous projects, both internally or with external clients. These relationships were established through time spent face-to-face before the remote work period. Lacking these relationships was described as a challenge, *"we already had a good, solid quantity of face-to-face work, a lot of common ground and respect for each other [...]. So that helped a great deal...when starting from scratch, [that] makes it a much bigger challenge."*

Participants highlighted both the positive and negative impacts remote work had on teamwork, despite most participants having a positive sentiment overall towards remote work. This insight may be contradictory, but one possible explanation that emerged is that participants perceive the negative impacts of remote work on teamwork as solvable given a future of remote work that is at least partially co-located.

In summary, most participants described that remote work made it challenging to build and maintain interpersonal relationships with their coworkers, which we hypothesize impacts the ability of multidisciplinary teams to collaborate on CASD work.

4.1.5 | One-off innovation

Hobday describes product profiles, or products where one version builds off the previous one (think iPhones), in differentiating mass-produced goods from CoPS.[17] He explains how simpler products with product lines benefit more from learnings from past product versions, which is less common in CoPS as each product or system tends to be uniquely designed for a specific customer and use.[17] This quality, called 'one-off innovation,' means that the design processes followed in CASD work are different, uniquely impacting the remote work experience. As each new product/service is innovative in some way, the conceptual design phases (Pre-Phase A and Phase A in the NASA classification) are fundamental, and our participants describe a lack of efficient virtual tools for replicating these highly collaborative, creative activities online.

For example, participants shared that live drawing tools (i.e., virtual whiteboard alternatives) are inadequate for conceptual or graphical engineering activities. Drawing conceptual designs on a whiteboard while co-located in a room was highlighted as a productive practice now hindered because access to appropriate alternative technologies is lacking. Specifically, when asked about the design phases, participants noted that Pre-Phase A and Phase A were negatively impacted by remote work, primarily because this conceptual work was tightly coupled, thus requiring rapid feedback and strong teamwork, which are hindered in remote work scenarios, as previously discussed. Participants particularly noted that conceptual work is much more efficient when they can quickly run an idea by their desk neighbor. One participant describes their challenges in completing early-stage conceptual work, "*I was on a lot of proposal efforts, and there's a lot of conceptual work in proposals. And it was a challenge to kind of explain what you were thinking of and communicate that to someone without having easy access to my CAD tools because it would just chug down on the bandwidth, on my computer... the tools that we were using like the Zoom annotate, and they weren't really that great...So trying to discuss technical solutions for proposals and conceptual paths forward was a challenge as well.*"

4.1.6 | High cost of experimentation

Lastly, Hobday describes how CoPS are usually comprised of expensive electric and mechanical components, which means that it is harder to iterate, or experiment with different designs, as each prototype can be costly.[17] Combined with the one-off nature of the innovation, this means that designers must work carefully during the conceptual design phase, utilize software and computation testing methods, and conduct physical tests frequently during the manufacturing process. In the NASA Systems Engineering process, this refers to the AIT activities that take place in Phases C and D. Primarily, our participants discussed how the frequent testing needed in this type of work made it challenging to work remotely successfully and resulted in communication issues between engineers and technicians.

Phase D particularly suffers during remote work. As discussed in the background, Phase D involves AIT and hardware work, so all the challenges associated with those aspects of engineering apply primarily to this phase. Our participants reported far more challenges of AIT caused by remote work than benefits to AIT. One participant, working on a Phase D program overseeing the mechanical work, elaborated extensively on challenges throughout their interview, stating, "*I don't see [current operations] as a viable way of being able to work remotely now or moving forward.*"

During the remote work period, AIT work still occurred on-site, as programs would halt or be delayed if in-person work was blocked in this respect. Those on-site were typically technicians, whereas the engineers worked remotely, though this varied by role and personal preference. The main impetus for any participants being on-site was to work with hardware, as per company policy. Examples of on-site hardware work include working on or supporting testing and hardware activities and setting up and collecting 3D-printed components. Given this, there are challenges associated with AIT, but its core function remains fundamentally unchanged. One suggestion to this challenge, which our participants did not discuss, but we may see emerge in coming years, is using robots for AIT activities. As robotic capabilities advance, studies suggest they may replace humans for some AIT activities, enabling Industry 4.0.[50]

One aspect of AIT that has not changed in remote work conditions is testing protocols. The company has an established corporate process for conducting testing with a group of personnel required, and this has not changed with remote work. Other AIT-related tasks that do not require co-located work also have not changed, such as reviewing relevant documents and creating tests. Meetings to address assembly problems are also able to proceed via video calls.

As mentioned previously, challenges with AIT and hardware center around how it is difficult to communicate about features of physical hardware when not co-located. One participant described the challenge of remotely conducting the process of solving assembly problems on-site. They described referencing several visual sources of information and working with the technician: *"you're like sitting [by] a problem, looking at hardware, looking at a reference hardware, looking at the drawings and looking at a CAD model and to share that via Zoom, it's just impossible. There's no way."*

In contrast, Phase E (operations) appears to be positively impacted by remote work. The findings on this phase are primarily from Team A's experiences, though there are other mentions of this in the study. In particular, the nature of aerospace systems operations supported by the company already incorporates various elements of remote work: collaboration between geographically dispersed teams and the naturally remote operation of the space systems. As one senior participant expressed, *"supporting things remotely is certainly a well-proven capability from our line of work."* The conclusion is that the remote work period presented new tools and strategies to collaborate and forcefully motivated their adoption. A key exception to this conclusion is that ongoing testing activities to support operations will face the same negative impacts as AIT and hardware work.

In summary, the nature of frequently testing hardware components as required in CASD work challenges the ability of these team members to work remotely. Some testing always has to happen on-site, which can cause communication issues between those on-site and those working remotely. While some testing could be conducted over video calls, our participants shared that this isn't a viable solution in the long term.

5 | DISCUSSION, IMPLICATIONS AND FUTURE WORK

This study presents the challenges engineers designing complex aerospace systems experienced when working remotely during the COVID-19 pandemic. We have structured these findings around the characteristics of complex system development[17] to describe how this type of work specifically may be challenging to complete remotely, as well as to provide strategies that our participants derived to overcome these challenges, and to highlight areas for future work. However, numerous other theories within the Systems and Design Engineering field can further elucidate the challenges faced by complex system designers working remotely, predict what challenges we might continue to see, what the outcomes of these challenges are, and suggest critical areas for future research. Here, we discuss two theories: the mirroring hypothesis[24,51] and the impact of shared understanding.[52]

The mirroring hypothesis[51] states that the formal structure of an organization that designs systems should mimic the technical structure of the system being designed.[24] Scholars have empirically tested this by analyzing whether ties—such as communication, co-location, or employment relations—correspond to technical dependencies within the product or system.[24] A recent review of studies testing this hypothesis found strong evidence that a product/system's technical structure corresponds to the organization's structure in studies of industries and firms.[24] Further, they found that most firms who explicitly chose to model their structure based on the technical dependencies of the product/system performed well, and those organizations that failed at this mirroring performed poorly. The study also finds that communication between individuals is the most common way of measuring a tie in an organization; however, when it is challenging to measure communication directly, the proximity of co-location is often used as a proxy. This point explains how we may expect remote work to impact CASD. We found that informal communication was lost when our participants began working remotely, impacting their ability to work on tightly coupled tasks and receive feedback on design iterations. Extending this finding, if this informal communication made up much of the interactions between individuals and teams—if physical proximity and the ensuing informal communication were relied on for creating organizational links between the products' interacting elements—long-term remote work may cut some of these ties within the organization, thus harming the mirroring between the organization and the product. In turn, this may mean that subsystems within the larger product/system may no longer integrate as they should, and task dependencies could cause delays in development. Some of the findings in our work, such as slow design feedback, may be warning signs for these outcomes. We motivate future work to study the mirroring hypothesis in CASD and how mirroring is affected by remote work practices. Scholars can analyze the organizational architecture of organizations moving from entirely remote practices to hybrid or in-person schedules to investigate the impact these changes have on mirroring and overall project success.

The second theoretical body of work we can contextualize our findings within is the study of shared understanding in design teams.[53] Shared understanding is the degree of overlap of each team member's belief of the goals, processes and context of the task at hand.[30] Shared understanding is an outcome of effective communication within teams,[53] and due to the changes to communication when working remotely, many studies have looked at how remote teams build shared understanding.[30,53–55] A number of conclusions have been made about what contributes to shared understanding, such as team spirit,[30,54] shared experience,[30,54] trust between team members,[54] transparency,[54] question asking,[53] having the opportunity to learn about each other over time,[30] and sharing knowledge.[30] Our interviewees described many of these contributing factors as harmed during remote work—for example, our participants shared that it was challenging to ask questions and get feedback, and informal communication where knowledge sharing typically happens disappeared. Thus, we can hypothesize that building and maintaining shared understanding in system design teams will be challenging when working remotely. A strong shared understanding is linked to improved performance; specifically, it allows teams to predict the behaviours of other members and efficiently use resources and efforts, reduces implementation errors, increases the motivation of team members, and reduces conflict.[30] Without a strong shared understanding of the goals, tasks, processes, team interactions, and team members themselves, the systems designed by CASD teams may suffer. While shared understanding has been studied in already geographically dispersed teams,[53,55] future work can analyze how shared understanding varies as teams co-locate more or less often, and how we can implement the contributing factors of shared understanding in remote environments.

Specific areas of future study that this work motivates include: solutions for the remote inspection of hardware; communication platforms, and how they should be adopted; the impact of the presence or absence of video in virtual meetings, and; cultivating informal communication in remote and hybrid teams.

Specifically in terms of informal communication, which we heard a lot about in our interviews, we motivate further research into the balance between flexible working schedules and creating opportunities for this type of communication. Ten of the 12 participants we interviewed would like to continue remote work in some capacity, and many mentioned a balance of remote and co-located work, such as working in office 2–3 days a week to communicate with colleagues and having a few days a week for concentrated work at home. Suppose employees choose a hybrid of co-located and remote work in the future. In that case, employees who are co-located on a given day can engage in informal communication but will exclude employees working remotely. Similarly, those who are co-located may not be able to visit those working remotely at their desks, eliminating some benefits of co-located communication. In fact, a recent study found that the adverse effects of remote work are not eliminated by you being in-office, but by your surrounding team and department being co-located.[56] One possible mitigation to this challenge suggested by participants is synchronizing remote working schedules, and designating which days all team members should be co-located. However, this mitigation does not address problems between teams. The authors see this as a significant area for future work and perhaps one of the biggest challenges for hybrid remote work after the COVID-19 pandemic.

Lastly, this exploratory study begins to develop a framework for remote CASD work, which can be the basis of future quantitative studies to assess the direct impact of work design choices on organization and system outcomes.

6 | LIMITATIONS

This study aims to provide a preliminary understanding of remote work in the CASD context. The exploratory nature of this aim warranted a qualitative investigation via semi-structured interviews. Future work will aim to test the generalizability of the findings outside of this setting, with a larger and more diverse sample. Specifically, with women comprising only one-third of this study's participants, the representation of women's perspectives may be reduced or lost in the results. Interview studies generally draw on small sample sizes and rely on participant self-assessment, memory and reflection (salience).

Further, this study focused on remote work's challenges rather than benefits. The study focused on one company to provide a deep understanding of that context of the work; however, this prevents the identification of any company-specific effects. In this study, not all design phases were represented equally, and a future study may therefore be able to specify challenges by phase better.

The interviews took place 7 to 11 months into the remote work period. Therefore, the participants were past the transition phase of this work and had the time to adapt to remote work and establish processes and routines. However, the timeframe still limits this study to only observing the near-term impacts of virtual work via this study; there may be uncaptured, longer-time-scale effects of this mode of work still to be uncovered.

7 | CONCLUSION

The impact of remote work on engineers working on complex system development in the aerospace sector has been previously understudied, but in the wake of learnings from COVID-19 restrictions, it is anticipated to grow. CASD involves tightly coupled work; thus, the communication challenges associated with virtual work are expected to have a significant impact. The present study has endeavored to explore this topic and uncover particular challenges of remote work unique to CASD work via a series of semi-structured interviews at a major aerospace corporation.

This qualitative study revealed that while flexible working styles are feasible for CASD work, virtual work also negatively impacts relationships between teammates in tightly coupled work, with some positives associated with teams that were previously working remotely (due to geographic distribution). Based on the characteristics of CASD work, the findings show that a lack of informal communication challenges cross-team collaboration; design feedback was slow, or impossible sometimes; it was challenging to demonstrate systems to customers and suppliers; interpersonal relationships, which help to bridge discipline divides, were harder to maintain; the required conceptual design lacked appropriate virtual tools; and testing hardware products and systems required close virtual communication between technicians and engineers.

Though CASD work is tightly coupled, technically challenging, and highly uncertain, some of the challenges experienced are similar to those reported in other engineering contexts. This study motivates future work that the authors argue is important to address to improve further the productivity, outputs, and experience of virtual work for CASD engineers.

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DATA AVAILABILITY STATEMENT

Author elects to not share data.

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REFERENCES

1. Bailey DE, Leonardi PM, Barley SR. The lure of the virtual. *Organ Sci*. 2012;23(5):1485-1504. doi:10.1287/orsc.1110.0703
2. Cameron B, Adsit DM. Model-based systems engineering uptake in engineering practice. *IEEE Trans Eng Manag*. 2020;67(1):152-162. doi:10.1109/TEM.2018.2863041
3. Fakhar Manesh M, Pellegrini MM, Marzi G, Dabic M. Knowledge management in the fourth industrial revolution: mapping the literature and scoping future avenues. *IEEE Trans Eng Manag*. 2021;68(1):289-300. doi:10.1109/TEM.2019.2963489
4. Lumseyfai J, Holzer T, Blessner P, Olson BA. Best Practices framework for enabling high-performing virtual engineering teams. *IEEE Eng Manag Rev*. 2019;47(2):32-44. doi:10.1109/EMR.2019.2916815
5. De Weck O, Krob D, Lefei Li, Lui PC, Rauzy A, Zhang X. Handling the COVID-19 crisis: toward an agile model-based systems approach. *Syst Eng*. 2020;23(5):656-670. doi:10.1002/sys.21557
6. Ben YA. Check out NASA employees ' super cool work-from-home setups. 2020. Accessed April 13, 2021. https://www.timeout.com/usa/news/check-out-nasa-employees-super-cool-work-from-home-setups-042020
7. Blanco S, How Mercedes-Benz Engineers Tackle Work from Home. 2020. Accessed April 13, 2021. https://www.caranddriver.com/features/a32380268/mercedes-benz-engineers-work-from-home/
8. Vincent J, Working from Home, with Robots. 2020. Accessed April 13, 2021. https://www.theverge.com/21285010/boston-dynamics-spot-engineers-2-0-upgrade-working-from-home
9. Morrison-Smith S, Ruiz J. *Challenges and Barriers in Virtual Teams: A Literature Review. 2*. Springer International Publishing; 2020. doi:10.1007/s42452-020-2801-5
10. Madni AM, Sievers M. Systems integration: key perspectives, experiences, and challenges. *Syst Eng*. 2013;17(1):37-51. doi:10.1002/sys
11. Tripathy A, Eppinger SD. Organizing global product development for complex engineered systems. *IEEE Trans Eng Manag*. 2011;58(3):510-529. doi:10.1109/TEM.2010.2093531
12. Sia C-L, Teo H-H, Tan BCY, Wei K-K. Effects of environmental uncertainty on organizational intention to adopt distributed work arrangements. *IEEE Trans Eng Manag*. 2004;51(3):253-267. doi:10.1109/TEM.2004.830859
13. Szajnfarber Z, Gralla E. Qualitative methods for engineering systems: why we need them and how to use them. *Syst Eng*. 2017;20(6):497-511. doi:10.1002/sys.21412
14. Martins LL, Gilson LL, Maynard MT. Virtual teams: what do we know and where do we go from here? *J Manage*. 2004;30(6):805-835. doi:10.1016/j.jm.2004.05.002
15. Harris D. Supporting human communication in network-based systems engineering. *Syst Eng*. 2001;4(3):213-221. doi:10.1002/sys.1017
16. Marzi G, Ciampi F, Dalli D, Dabic M. New product development during the last ten years: the ongoing debate and future avenues. *IEEE Trans Eng Manag*. 2021;68(1):330-344. doi:10.1109/TEM.2020.2997386
17. Hobday M. Product complexity, innovation and industrial organisation. *Res Policy*. 1998;26(6):689-710. doi:10.1016/S0048-7333(97)00044-9
18. Magnusson T. From CoPS to mass production? Capabilities and innovation in power generation equipment manufacturing. *Ind Corp Chang*. 2005;14(1):1-26. doi:10.1093/icc/dth042
19. Prencipe A. Breadth and depth of technological capabilities in CoPS: the case of the aircraft engine control system. *Res Policy*. 2000;29:895-911.
20. NASA. N System Engineering Handbook Revision 2. Natl Aeronaut Sp Adm. 2016:1-297. https://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook_0.pdf
21. Eppinger SD, Joglekar NR, Olechowski A, Teo T. Improving the systems engineering process with multilevel analysis of interactions. *Artif Intell Eng Des Anal Manuf AIEDAM*. 2014;28(4):323-337. doi:10.1017/S089006041400050X
22. Larson WJ, Wertz JR. *Space Mission Analysis and Design*. 3rd ed. Microcosm; 1999.
23. Fortescue P, Swinerd G, Stark J. *Spacecraft Systems Engineering*. 4th ed. John Wiley & Sons, Inc; 2011.
24. Colfer LJ, Baldwin CY. The mirroring hypothesis: theory, evidence, and exceptions. *Ind Corp Chang*. 2016;25(5):709-738. doi:10.1093/icc/dtw027
25. Tenopir C, King DW. *Communication Patterns of Engineers*. IEEE Press, John Wiley; 2004. doi:10.1002/0471683132
26. Jiang JJ, Huang WW, Klein G, Tsai JC-An. The career satisfaction of IT professionals with mixed job demands. *IEEE Trans Eng Manag*. 2020;67(1):30-41. doi:10.1109/TEM.2018.2870085
27. May A, Carter C. A case study of virtual team working in the European automotive industry. *Int J Ind Ergon*. 2001;27(3):171-186. doi:10.1016/S0169-8141(00)00048-2
28. Gilson LL, Maynard MT, Jones Young NC, Vartiainen M, Hakonen M. Virtual teams research: 10 years, 10 themes, and 10 opportunities. *J Manage*. 2015;41(5):1313-1337. doi:10.1177/0149206314559946
29. Gibson CB, Gibbs JL. Unpacking the concept of virtuality: the effects of geographic dispersion, electronic dependence, dynamic structure, and national diversity on team innovation. *Adm Sci Q*. 2006;51(3):451-495. doi:10.2189/asqu.51.3.451
30. Gibson CB, Cohen SG. *Virtual Teams That Work: Creating Conditions for Virtual Team Effectiveness*. John Wiley & Sons; 2003.
31. Babbie ER. *The Practice of Social Research*. 14th ed. Cengage Learning; 2015.
32. Whereby. Whereby. 2020. Accessed November 10, 2020. https://whereby.com/information/about-us/
33. QSR International. NVivo. 2020. Accessed November 14, 2020. https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home
34. Braun V, Clarke V. Using thematic analysis in psychology. *Qual Res Psychol*. 2006;3(2):77-101.
35. Corbin J, Strauss A. *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*. 3rd ed. SAGE Publications, Inc; 2008. doi:10.4135/9781452230153
36. Tomko M, Schwartz A, Nagel R, Linsey J, Aleman M, Newstetter W. "A makerspace is more than just a room full of tools": what learning looks like for female students in makerspaces. In: Proceedings of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 7: 30th International Conference on Design Theory and Methodology. ASME; 2018:1-16.

37. Loonam J, Zwiegelaar J, Kumar V, Booth C. Cyber-Resiliency for digital enterprises: a strategic leadership perspective. *IEEE Trans Eng Manag*. 2020;69:3757-3770. doi:10.1109/tem.2020.2996175
38. Shergadwala M, Forbes H, Schaefer D, Panchal JH. Challenges and research directions in crowdsourcing for engineering design: an interview study with industry professionals. *IEEE Trans Eng Manag*. 2020;69:1592-1604. doi:10.1109/tem.2020.2983551
39. Van Velzen E, Olechowski A. Investigation of remote work for aerospace systems engineers. *INCOSE Int Symp*. 2021;31(1):816-831. doi:10.1002/j.2334-5837.2021.00872.x
40. Hennig A, Topcu TG, Szajnfarber Z. So you think your system is complex?: why and how existing complexity measures rarely agree. *ASME J Mech Des*. 2022;144(4):041401. doi:10.1115/1.4052701
41. Ebert C, Jones C. *EMBEDDED SOFTWARE: Facts, Future*. IEEE Computer Society; 2009:42-52.
42. Ferguson S, Lai K, Chen J, Faidi S, Leonardo K, Olechowski A. Why couldn't we do this more often?": exploring the feasibility of virtual and distributed work in product design engineering. *Res Eng Des*. 2022;33(4):413-436. doi:10.1007/s00163-022-00391-2
43. Zoom CZV Zoom Video Communications. 2023. Accessed February 6, 2023. https://zoom.us/
44. Slack. Slack. 2020. Accessed November 14, 2020. https://slack.com/intl/en-ca/
45. Hölttä-Otto K, Björklund T, Klippert M, et al. Facing extreme uncertainty–how the onset of the COVID-19 pandemic influenced product development. *Int J Des Creat Innov*. 2022;11(2):117-137. doi:10.1080/21650349.2022.2157888
46. Nguyen M, Mougenot C. A systematic review of empirical studies on multidisciplinary design collaboration: findings, methods, and challenges. *Des Stud*. 2022;81:1-42. doi:10.1016/j.destud.2022.101120
47. Sonnenwald DH. Communication roles that support collaboration during the design process. *Des Stud*. 1996;17(3):277-301. doi:10.1016/0142-694X(96)00002-6
48. Birkinshaw J, Gudka M, D'amato V. The blinkered boss: how has managerial behavior changed with the shift to virtual working? *Calif Manage Rev*. 2021;63(4):5-26. doi:10.1177/00081256211025823
49. Lane J, Choudhury R, Bojinov I. Virtual Water Coolers: A Field Experiment on the Role of Virtual Interactions on Organizational Newcomer Performance. 2023.
50. Galizia FG, Bortolini M, Calabrese F. A cross-sectorial review of industrial best practices and case histories on Industry 4.0 technologies. *Syst Eng*. 2023:1-17. doi:10.1002/sys.21697
51. Henderson RM, Clark KB. Architectural innovation : the reconfiguration of existing product technologies and the failure of established Firms author, Rebecca M. Henderson Kim B. Clark Source : administrative science quarterly, Vol. 35, No. 1, Special Issue . *Tech Adm Sci Q*. 1990;35(1):9-30. http://www.jstor.org/stable/2393549
52. Badke-Schaub P, Neumann A, Lauche K, Mohammed S. Mental models in design teams: a valid approach to performance in design collaboration? *CoDesign*. 2007;3(1):5-20. doi:10.1080/15710880601170768
53. Cash P, Dekoninck EA, Ahmed-Kristensen S. Supporting the development of shared understanding in distributed design teams. *J Eng Des*. 2017;28(3):147-170. doi:10.1080/09544828.2016.1274719
54. Kniel J, Comi A. Riding the same wavelength: designers' perceptions of shared understanding in remote teams. *SAGE Open*. 2021;11(3):215824402110401. doi:10.1177/21582440211040129
55. Hinds PJ, Mortensen M. Understanding conflict in geographically distributed teams: the moderating effects of shared identity, shared context, and spontaneous communication. *Organ Sci*. 2005;16(3):290-307. doi:10.1287/orsc.1050.0122
56. Yang L, Holtz D, Jaffe S, et al. The effects of remote work on collaboration among information workers. *Nat Hum Behav*. 2021;6:43-54. doi:10.1038/s41562-021-01196-4

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