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Challenges and Opportunities in Remote Prototyping: A Case-Study during COVID-19

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Abstract

Collaboration is common practice within design disciplines and beyond. Brainstorming, discussions, and prototyping tend to occur within the same physical space. The reduction of human interaction during the COVID-19 pandemic disrupted these practices. In this paper, we focus on the possibilities and challenges of remote prototyping of four student teams by combining a double diamond approach with tools to overcome remote work challenges. The results were analyzed to understand crucial tools, advantages, and obstacles. The key challenges and opportunities were then identified and examined.

Keywords: collaborative design, prototyping, design tools, supportive technologies

1. Introduction

Since the outbreak of the COVID-19 pandemic, it challenged and continues to challenge existing infrastructure in all areas of life. The reduction of human interactions for virus control has become an effective measure (Silva et al., 2020). This measure for instance has a profound impact on creative businesses, design, and engineering projects, which often depend on joint physical prototype reviews and collaboration with large teams. This increased the complexity of design processes, especially with regards to prototyping. Therefore, several new studies have been to trial novel approaches and technologies in the design and engineering sector to enable teams to operate remotely (e.g., Virtual Reality, Real-time Collaboration Software, Teleconferencing tools, etc.) (Tucker et al., 2021; van Nifterik et al., 2021; Ye et al., 2021).

Multi-User Virtual Environments have been hypothesized in recent years as having the potential to enhance project work in distributed teams. VR, for example, can support teamwork in design projects. Studies have shown that virtual presences when co-creating increases engagement and purposeful prototyping, makes 3D visualization effortless that enables flexible free form creation, and that gesture-based interfaces provide a more natural and intuitive way of interaction with models in VR. Immersive 3D sketching allows rapid and flexible freeform creation of large and detailed 3D models (Nee et al., 2012). Clear benefits derive from the immersive visualization feature of CAD data in VR, which simplifies the decision-making process by uncovering design issues while providing an accessible commenting platform for aesthetics and functionality for reviewers with different skills and backgrounds. Several authors have identified areas that can pose a challenge to remote design projects: One study found that designers spend more time on designing the actual object or product, rather than engaging in discussions or idea generation, when using collaborative VR tools (Maher et al., 2006). Some authors argue that physical models increase the quality and originality of design solutions (Viswanathan and Linsey, 2010). Another paper raised the issue of the lack of testing scope for virtual

prototypes and the associated lack of data generated through physical prototypes. However, the authors suggested that the number of physical prototypes required to be reduced through virtual prototyping (Zorriassatine et al., 2003).
Existing literature shows that Multi-User Virtual Environments are powerful collaboration platforms to increase the efficiency of distributed design teams for the review stage. Examples include Gravity Sketch, Glue, or Mindesk. Similarly, other tools, digital or physical, also assist in remote collaborations such as sketching, video conferencing (e.g., Zoom), collaborative platforms (e.g., Miro, MS Teams), social media platforms (e.g., WeChat, Discord, Whatsapp), telerobotics, etc. (Tucker et al., 2021; Ye et al., 2021). The research community is however undecided on which and when those tools become particularly useful in a remote collaborative design project: Is VR only suitable for the early stages of concept design, due to lack of high-fidelity modeling accuracy? Is virtual prototyping only applicable in the detailed design stage once variety and ambiguity are reduced? Therefore, it is yet to be understood if digital-collaborative tools can serve as a space to facilitate a full design project from idea to delivery. This work reports on the limiting factors experienced by transdisciplinary teams during virtual, remote prototyping in different design phases. Four teams of designers and engineers have worked for six months on a complex design brief, using a range of contemporary collaborative VR apps, among other software platforms and techniques, to realize their ideas to fully built working models. We report on key learning and observations for distinctive design phases, based on insights, gained through interviews with all teams. Thus, the research questions to be answered are:

> RQ1: What are the challenges and opportunities with prototyping over a project lifecycle, during COVID-19 and in remote design engineering?
>
> RQ2: Can the double diamond approach combined with state-of-the-art tools such as VR technologies help overcome these challenges?

In Section II of this paper, the methodology of the study is outlined, followed by the results and its discussion in Section III. Section IV finishes with the conclusion and an outlook is provided.

2. Methodology

This study uses the remote collaboration project Tangibility between two higher education institutions as a test setting for data collection. It was a 6-month remote design engineering project for students of both institutions to collaborate in teams. The goal was to use VR Technology to solve a problem worth solving by going through a prototyping process from problem to solution. Even though other methodologies exist for similar student design teams such as Martins Pacheco et al. (2020), the Double Diamond design process model was used through phases of exploring an issue more widely (analysis/divergent thinking) and then taking focused actions (synthesis/convergent thinking) (Ball, 2019). The Double Diamond is divided into four phases namely: (1) Discover, (2) Define, (3) Develop, and (4) Deliver. In the first phase, the team tries to understand then assume what the problem is. In the second phase, the insights from the previous phase are used to define the requirements of the project. In the third phase, the design team searches for different solutions for the clearly defined problem. In the last phase, there is a synthesis of the results from the previous phase, rejecting the solutions that will not work and improving the ones that will. After this, the solutions are tested and validated with users. Nevertheless, Tschimmel (2012) suggests that the validated solutions should always be open for improvement, change, and further iteration. In addition, the Double Diamond approach has the following principles to keep in mind: (A) Put people first - Start with an understanding of the people using a service, their needs, strengths, and aspirations, (B) Communicate visually and inclusively - Help people gain a shared understanding of the problem and ideas, (C) Collaborate and co-create - Work together and get inspired by what others are doing, and (D) Iterate, iterate, iterate - Do this to spot errors early, avoid risk and build confidence in your ideas.
In total, 14 students participated in the project forming four teams with 3-4 students each from various backgrounds (Design, Mechanical Engineering, Electrical Engineering, Informatics, Human-factors Engineering, Business, etc.). Due to the project being run during a global pandemic, our students were situated in different parts of the world, working across 4 time zones during a period of 6 months. Each one of the teams received tutoring support from academics from both institutions as well as feedback from our

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commercial and technology partners, who also provided access to their VR software technology. Internally there was a team of six tutors from the higher education institutions and two from the commercial partner. The project started with a broad design brief that students had to further explore and refine:

> *"You will be using remote collaboration tools including Gravity Sketch and VR to design an innovative input device such as a haptic VR glove/controller or user interface, considering ergonomics, functionality, aesthetics, and user context."*

A project timeline was provided, which included design sprint weeks that concluded with interim presentations followed up by our tutor team's feedback. The double diamond approach was further rationalized into three project phases: (1) problem exploration (discover, define), (2) prototyping (develop), and (3) prototype delivery (deliver). The first two months (January - February 2021) were used for the problem exploration (1). The following two months (March - April 2021) were used for prototyping the solution (2), culminating in a remote presentation, where a digital prototype was required (mostly digital). The last two months (May - June 2021) were used to deliver the final proof of concept (3), where a physical prototype was requested. All students (except for one due to time and customs limitations within that country) had access to Oculus 2 VR goggles and were asked to use Gravity Sketch as part of their exploration process, but they were not limited to this platform and could use whatever else might satisfy their needs. All the teams used different collaboration tools, physical prototyping and digital prototyping with Gravity sketch and other modeling software for the development of this project.
This mixed methods research contains three distinct activities for data collection: (1) documentation of the design process from the teams at the end of each phase, (2) semi-structured interviews with design teams after the completion of the projects, and (3) online survey about the importance and use of tools and techniques based on the experience from their project. Two different methods were used to analyze the data, as they are quantitative (survey) and qualitative (interviews and documentation). The quantitative data was used to identify which tools and techniques were used in what phase and qualitative data were used to understand the challenges and opportunities of remote collaboration projects.

2.1. Documentation of the design process

The student design teams documented their activities with a presentation at the end of each phase. This included explaining the various activities they carried out during a phase and how they did it with an outlook into what follow-up has been planned. In addition, the Miro board, and all files regarding the project that every team used were submitted.

2.2. Semi-structured interviews with design teams

At the end of the project, semi-structured interviews were conducted with two team members speaking as a representative for the team. The interviewees were asked the following questions:

> *Q1: What were the challenges of remote collaboration in a transdisciplinary environment?*
>
> *Q2: What were the benefits of remote collaboration in a transdisciplinary environment?*

2.3. Online survey about the importance and use of tools and techniques

At the end of the project, a survey was used to collect information about the use and importance of different tools and techniques that the teams used. This questionnaire was divided according to the phases that the teams worked on.

3. Results

In this section, the results of going through the double diamond approach with four different student teams and the results from the survey and semi-structured interviews are shown.

3.1. Discover Phase

The first phase of double diamond aims to identify a problem and understand the people who have the problem in the process. Working in this phase comprises methods like Observation, Brainstorming,

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Design Thinking, Research, Fast Visualization, and User Diary. In the Tangibility project, the goal was to find a problem that can be solved using VR technology, specifically on the development of input devices that can enable remote collaboration on varied scenarios. Table 1 shows the outcomes in the discovery phase. Since this was an idea generation-heavy phase, clear forms of documentation and communication were at a premium. And this was reflected in the teams where they spent most of their activities on tools that enabled just that.

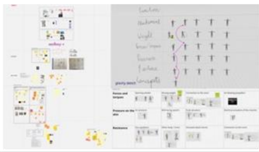
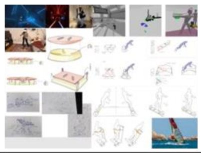
Table 1. Overview of Teams in the Discover Stage (I)

	Team 1	Team 2	Team 3	Team 4
Objective	To select a use-case in VR	To select a use-case in VR	To select a use-case in VR	To select a use-case in VR
Tools	Miro, Zoom, MS Teams, Google Drive	Miro, Zoom, MS Teams, Google Drive	Miro, Zoom, MS Teams, Google Drive	Miro, Zoom, MS Teams, Google Drive
Techniques	Ideation, Brainstorming, Design Thinking, Mind Maps	Ideation, Brainstorming, Design Thinking, Mind Maps	Ideation, Brainstorming, Mind Maps, Sketching	Ideation, Brainstorming, Design Thinking, Mind Maps, Team Canvas, Voting
Output	Collection of possible applications via Miro: (1) VR for space training, (2) Smell in VR, (3) Rehabilitation of Limb-loss with VR space training	Collection of possible applications via Miro: (1) VR for Rehabilitation, (2) AR/VR for Medical Training, (3) AR/VR for Interfaces	Collection of possible applications via Miro: (1) Shifting center of mass in VR, (2) Another Limb control in VR	Collection of possible applications via Miro: (1) Sexy VR, (2) Snowboard VR, (3) Yoga VR
Pictures				

3.2. Define Phase

The second phase of the double diamond concludes the first diamond and aims to use the insights gathered from the discovery phase to define the problem to be solved.

Table 2. Overview of Teams in the Define Stage (II)

	Team 1	Team 2	Team 3	Team 4
Objective	Finalize on one application area and define all functionalities	Finalize on one application area and define all functionalities	Finalize on one application area and define all functionalities	Finalize on one application area and define all functionalities
Tools	Miro, Zoom, MS Teams, Google Drive	Miro, Gravity Sketch, Zoom, MS Teams, Google Drive	Miro, Gravity Sketch, Zoom, MS Teams, Google Drive	Miro, Gravity Sketch, Rhino, Zoom, MS Teams, Google Drive,
Techniques	Sketching, Low Fidelity Prototyping	Sketching, VR Sketching, Low Fidelity Prototyping	Sketching, VR Sketching, Low Fidelity Prototyping	Sketching, VR Sketching, Low Fidelity Prototyping
Output	Weather Simulation: Selection of key functions for the proposed solution and vision video how the product might work	Biopsy Training: Selection of key functions for the proposed solution and vision video how the product might work	Salsa Training: Selection of key functions for the proposed solution and vision video how the product might work	Board Sports: Selection of key functions for the proposed solution and vision video how the product might work
Pictures				

Working in this phase comprises methods like: Focus Groups, Assessment Criteria, Comparing Notes, and Customer Journey. In the Tangibility project, the teams concluded this phase by choosing one application area for VR technology and defining the functionality for the proposed solution. Table 2 shows the outcomes in the define phase. This phase is heavy on research framing and the collaboration emphasis was reduced to a certain degree, but the teams, in this case, had to communicate with the users to understand the problem better, which led to difficulties in conducting user surveys and interviews online. This was also the phase where the core ideas need to be sketched or designed which made collaboration a challenge due to design locks for multiple users. This was overcome to a certain degree through VR sketching on Gravity sketch and cloud-based CAD software like Autodesk Fusion. Of particular note was the VR morphological chart from Team 3, where every idea concept was sketched in full human scale along rows and was compared to every other idea, which served as an excellent ideation tool.

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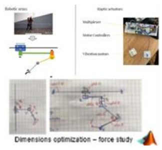
3.3. Develop Phase

The third phase of double diamond aims to search for alternative solutions for the clearly defined problem. Working in this phase to brainstorm design concepts and test different solutions, comprises methods like User Story, Service Blueprints, Physical Prototyping, and Feature Testing. In the Tangibility project, the teams concluded this phase by proposing a solution concept comprising different functionalities in high-quality renders (virtually). Table 3 shows the outcomes in the development phase.

Table 3. Overview of Teams in the Develop Stage (III)

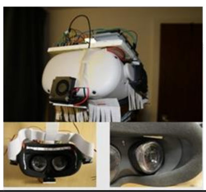
	Team 1	Team 2	Team 3	Team 4
Objective	Concrete application: We simulate weather to fight winter depressions	Concrete application: We create an immersive AR biopsy training	Concrete application: We create an VR Salsa Dancing Partner	Concrete application: We create a VR controller for Board sports
Tools	Gravity Sketch, CAD (Autodesk Fusion 360), Zoom, MS Teams, Google Drive	Gravity Sketch, CAD (Autodesk Fusion 360), Zoom, MS Teams, Google Drive	Gravity Sketch, CAD (Autodesk Fusion 360), Zoom, MS Teams, Google Drive	Gravity Sketch, CAD (Autodesk Fusion 360), Zoom, MS Teams, Google Drive
Techniques	CAD, Low Fidelity Prototyping, Morphological Analysis	CAD, Low Fidelity Prototyping, Morphological Analysis	CAD, Low Fidelity Prototyping, Morphological Analysis	CAD, Low Fidelity Prototyping, Morphological Analysis
Output	High Quality Renders of the proposed concept: Holistic experience, Ambient conditions (wind, heat, light), Mobile experience, Directionality	High Quality Renders of the proposed concept: Allows use of real biopsy needles and provides haptic feedback of different resistance for immersive AR biopsy training.	High Quality Renders of the proposed concept: Robotic arms and wearable to practice salsa dancing	High Quality renders of the proposed concept: Board controller for super board game. User Story how to use the game.
Pictures				

The use of VR for remote collaboration was particularly dominant in this case where the teams could add to feature attributes in a digital setting. The use of VR also had a pronounced increase among the Teams since they presumably had worked longer in the platform which allowed for better acclimatization.

3.4. Deliver Phase

The last phase of the double diamond concludes the second diamond and aims to test different solutions and decide on the final set of features to be implemented while improving already implemented functionalities. Working in this phase to finalize, produce, and launch the product, comprises methods like Phasing, Integration, Evaluation, User Testing, and Feedback. In the Tangibility project, the teams concluded this phase by realizing a proof of concept of the proposed solution (real). Table 4 shows the outcomes in the delivery phase.

Table 4. Overview of Teams in the Deliver Stage (IV)

	Team 1	Team 2	Team 3	Team 4
Objective	Simulate summer weather. Integrate all features into a single concept.	Build a functional Prototype of force feedback unit for AR.	Build a small demonstrator of the robotic system.	Develop a first usable game concept with contoller interface.
Tools	Hardware Development Tools (Normal hand tools, 3D Printing, heat sensors, soldering iron, Microcontroller, Electronics), Zoom, Microsoft Teams	Hardware Development Tools (Normal hand tools, 3D Printing, heat sensors, soldering iron, Microcontroller, Electronics), Zoom, Microsoft Teams	Hardware prototyping, drawing, simulation, Low-fi Prototype in GS, MATLAB, Microsoft Teams	Hardware Development Tools (Normal hand tools, 3D Printing, heat sensors, soldering iron, Microcontroller, Electronics), Zoom, Microsoft Teams
Techniques	High Fidelity Prototyping and User Testing	High Fidelity Prototyping and User Testing	High Fidelity Prototyping and User Testing	High Fidelity Prototyping and User Testing
Output	A series of VR multi-sensory add-ons to simulate different ambient conditions with a special focus on whole face experience. Whole face experience: Inside/Outside headset	Allows to use real world biopsy needles and provides haptic feedback of different resistance for immersive AR biopsy training Targeted at university students in educational setting.	Robotic System attached to a rail system mimicking the salsa dance partner movement. A Belt gives feedback to the user while wearing a VR Headset.	User Interface and User Experience for the Game in Unity. First controller board interface tracking the movement and sending information the game.
Pictures				

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The emphasis on this phase is on prototype building, and due to the limitations of remote collaboration, the prototype features were predominantly built individually and then integrated by one person, who also acted as the test user for validation. The shortcomings of in-person testing were most felt in this area. The lack of realistic haptic feedback devices in the market also ruled out the use of digital prototypes for user testing since it was infeasible to produce physical prototypes that can be sent out for end-user testing.

3.5. Results from the interviews

Having completed the four stages of development with the four teams, we conducted interviews to collect feedback on their product development process and on the challenges and opportunities of doing an online design project that requires a considerable collaborative effort.

The challenges were noticeably higher at the very beginning of the project, where all students and most of the instructors were getting used to the "new normal". During the discovery phase, finding platforms that allow for varying levels of interactions to discuss ideas, organize meetings, and schedule input sessions from instructors proved to be particularly challenging. This is supported by the following quote of Team 1:

> *"We used mostly two platforms, Google and Miro. Of course, we used (Microsoft) Teams for presentations, file storage [...] so there are three platforms. If it's one, it must be amazing."*

There were teams that found alternative and unified tools like Slack for data exchange that mimics a chat function. As quoted by Team 3:

> *"We were using Miro for ideation, but at the same time, we were communicating through Slack. I suppose in the beginning we were using Slack as a platform to share some prior art and some related papers and research."*

Some of the other challenges as stated by the teams were finding a unifying platform and how to incorporate classical methods of ideation and product sketching on a virtual platform. This is supported by a quote from Team 2:

> *"[...] I have my color pencil and that is what I'm used to because now I'm not in my home, so, the tools that I can use are not so much. I tried to use Photoshop or Illustrator to draw, but it's a little bit time-consuming and output is not so good [...], I come back to using the sketch with color pencil and sometimes I used cardboard for modeling."*

As highlighted in the previous quote, physical sketching seems to be the most common way of generating concepts. Some other teams however found more innovative methods such as Team 4:

> *"I would normally just sketch it and then hold it in front of the video. I find it quick using paper."*

In addition, the team limited the complexity by sticking only to two different tools:

> *"I think we were only using Zoom and Miro."*

A key lesson here was people tended to stick to techniques they were used to and transferred physical sketches through digital means. There was very limited use of VR sketching as the learning curve was also steep at the beginning and when questioned about the lack of VR tools at these stages, one team summarized:

> *"I think I like defining rules, and I mean staying very clearly in the beginning. What should be shared where and then doing a better job explaining a little bit more [...]."*

During the define phase, after the students had more practice with the VR equipment, the digital interaction sessions started to increase. The collaborative mode from Gravity Sketch was specifically appreciated since there was the opportunity to collaboratively work on ideas on a single canvas. This

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was a new experience for many, and the students got into the novelty of the approach and used it extensively, as quoted by Team 1:

> *" So, in the later stage, we used Gravity Sketch because there was a collaborative mode, to sketch together and generated ideas but we also did CAD models that we could prototype."*

Team 2 started testing more complicated designs such as mechanism design with the same, as indicated by the following quote:

> *"[...] We met in Gravity Sketch to try to check out the mechanism and to model them."*

This did not mean the classical methods for defining the use cases were ignored since many teams also used online surveys, morphological boxes to assimilate different concepts, and physical, low-fidelity prototypes to check basic concepts and then conveyed the results to their teams.
The develop phase was one of the most challenging for the teams as they had to source different parts and coordinate on feature development. This was heavily mitigated by the global supply chain recession due to the pandemic. Remote working also severely impeded the teams' progress. Some of the steps deployed by the teams to reduce the challenges of remote collaboration and working on physical prototypes from different places where the extensive use of VR collaborative platforms like Gravity Sketch which allowed for collaborative prototype design, as stated by Team 4 in the following quote:

> *" Sketching was always a good beginning when I think about a particular feature. We thought about why we needed this feature and needed to have a visual. After this, we met in Gravity Sketch on a weekly basis. In GS we would build something tangible."*

Low-fidelity prototypes were extensively used, either in a digital format using cloud-based 3D CAD tools or Gravity Sketch as Team 3 states:

> *"[...] it's easier to visualize it (in Gravity Sketch) as it will be at the end as on the screen because it's really on the virtual reality world, so it's really as if it were there next to you, so it's real. Much better on the VR screen than on the computer screen."*

Other methods included delegating feature exploration to team members given the availability of prototyping resources and then trying to estimate feature integration on online collaborative platforms like Miro and Zoom/MS Teams. For example, Team 1 states:

> *"[...] because our prototypes evolved [features] like airflow, heating and how it works cannot be tested in a digital way, so we needed to make physical prototypes. ... if I have like paper or form, I may just do it directly without CAD. We conducted the same test, but we used different approaches. Depending on the components we could get and our personal preferences"*

This clearly points to collaboration on physical prototyping of features was challenging but certainly was possible.

3.6. Results from the survey

In the survey, the teams were asked what tools and techniques (from "Never (1)" to "Every Day (5)") they had used in each phase of the project. In addition, the teams were asked to rate the importance (from "not at all important (1)" to "Extremely important (5)") of these tools for the respective project phase. The results can be seen jointly in a graph in Figure 1. In the graphs, the respective teams are color-coded and the tools and techniques are indicated by the icon shape.
Here, we can see that the teams vastly differed in the use of prototyping methods and tools depending on the phases, but the communication tools such as video conferencing tools (e.g., MS Teams, Zoom) and collaboration tools (e.g., Miro) were pretty much consistently used throughout. However, it can be noted that collaboration tools were rated less important towards the end while also being used less frequently. The use of 3D CAD (e.g., Gravity Sketch) was at its highest during the second phase

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(Prototyping) as it provided an ideal platform for realizing ideas and prototypes in 3D while allowing for simultaneous collaboration of all teams' members and worked as a virtual meeting room to brainstorm features of the prototypes. This was also aided by the fact that the teams grew increasingly skilled in using VR platforms for design over time. However, this was limited to low-fidelity prototypes, and they had to switch to traditional CAD tools and physical prototyping, once high-fidelity prototypes were required, especially in the latter delivery stage.

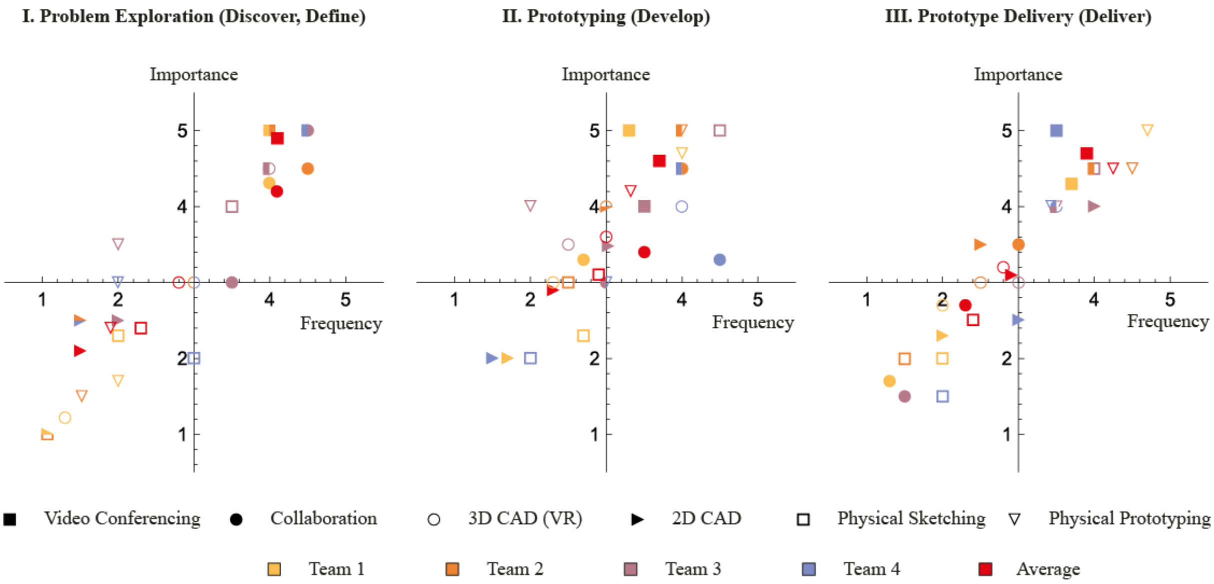

Figure 1. Comparison of the Usage and Importance of Tools and Techniques from the Teams

In addition, a survey (on a 1 to 5 Likert scale) was conducted on the challenges and opportunities the teams deemed the highest, which is summarized in Figure 2. The teams were clearly motivated to participate in an international collaboration project despite the limitations dictated by remote collaboration during a pandemic. Team composition (involving the right people) and increased individual creativity were put at a premium to overcome technical challenges via innovative ways. The results in Figure 2 also show that the double diamond framework and its associated techniques can be adapted to modern tools that saw a rise during the pandemic for implementation in a remote setting. This is an important insight on the validation of classical frameworks with changing socio-technical contexts and their associated challenges.

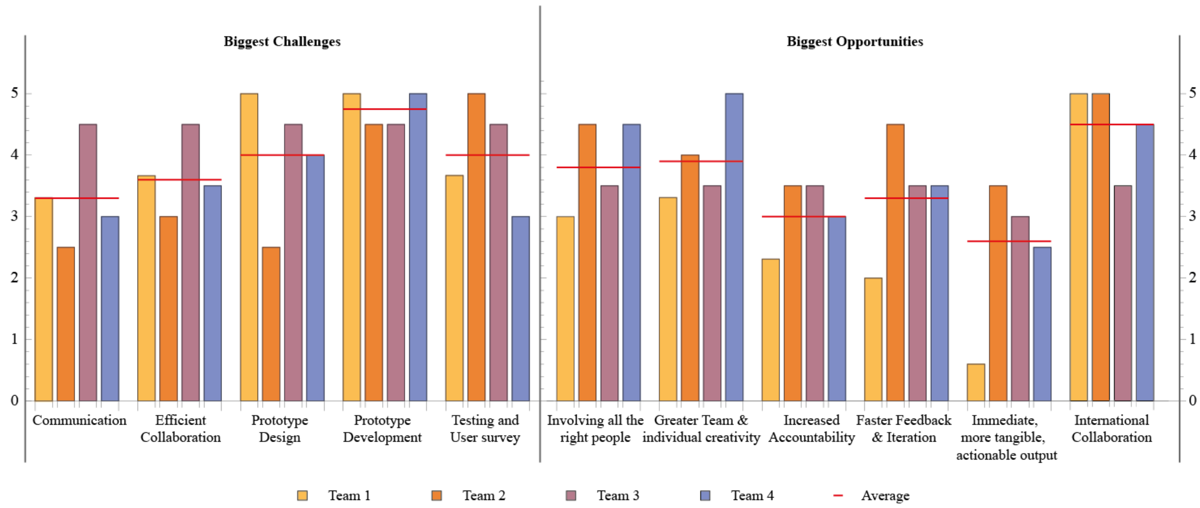

Figure 2. Survey Comparison of the Biggest Challenges and Opportunities in the Project faced by the four teams

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The biggest challenges the teams faced were physical prototyping development and in user requirements generation and testing, where access to adequate tools from home, reduction on the global supply chain, and limited access to manufacturing all played a role. Testing and user feedback surveys that would have been typically done on-site or in-person had to become virtual, which limited the extent of feedback the teams could get on their perceived products and their associated features. So, a way to test their virtual prototypes or even their individual features with one larger audience is expected to have vastly helped the outcome. However, a large pain point of remote collaboration, which is deemed to be the communication and efficient collaboration was greatly reduced using tools such as MS Teams/Zoom, Miro, and Gravity Sketch, which made sure that all mitigating communication-related factors, were at a minimum.

4. Conclusion & Outlook

This paper contributes to the question on the challenges and opportunities in remote design engineering projects during covid-19 that require prototyping. Specifically, this study investigated the usage of different tools and techniques used in remote design engineering projects during covid-19 restrictions. Four student teams' development process documentations were used to identify the importance and frequency of tools and techniques used in the projects. The double diamond approach hence seemed to have worked well in the first three stages with the last physical development being the biggest challenge. Based on the survey and interviews, communication was expected to be one of the biggest pain points but did not turn out to be true. Instead, teams had problems with realizing physical prototypes because of limited access to tools, infrastructure, and supplier problems. Apart from the mentioned conditions, the teams struggled with feature integration, due to mostly individual isolated development meetings on a weekly basis with their team while hindering rapid prototyping and quick communication. The biggest challenges hence were deemed to be physical development of the products, and later its integration, combined with efficient surveying techniques of end-users. However, it also gave rise to opportunities to discover and utilize the new/previously underutilized collaboration tools such as VR, cloud-based CAD and other tools such as Zoom and Miro proved to be highly useful. And moving the whole collaboration online led to an international collaboration from remote sites which was previously a very hard feat to execute.

Relatively new communication and collaboration tools were placed at a premium as they facilitated the communication in the team (e.g., Zoom, MS Teams, Miro, etc.). 3D CAD Tools (e.g., VR Gravity Sketch) helped and reduced the disadvantages of remote collaboration on prototype development by allowing the team to work together in real-time. A unifying platform that allowed for carrying out ideation sessions, collaborative documentation, communication (video/conference calls), low-fidelity prototyping, and reasonably accurate CAD is required to make the first two phases (first diamond) more successful. In these stages, the teams struggled to grapple with all the different platforms and how to integrate them into a cohesive design strategy. During the latter stages where the teams had to do physical prototyping, the pandemic had a greater effect since it was not limited to tool or software used, but more due to lack of infrastructure and supply chain issues. Which is near-impossible to plan for on a time-constrained project. The results show that the different tools and techniques successfully support remote development projects that highlight a lot of opportunities but also challenges to be solved, i.e. abundance of different platforms without proper integration. However, a major area for improvement could possibly be in the advancement of building high-fidelity digital prototypes that can be tested in VR, which would require an advance of haptic feedback technology that allows for at least increased physical interaction with products and experiences in such remote development scenarios.

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