From Universe to Metaverse: A Leap Into Virtual Collaboration at NASA JPL

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***Abstract*—During the upheaval of the COVID-19 pandemic, the Jet Propulsion Laboratory (JPL), like most organizations, found itself trying to adjust to a new reality of remote and hybrid work. An emerging concept that seemed promising was the notion of a metaverse—a collection of technologies that could create, or recreate, our physical spaces and interactions. In response, JPL experimented with a rollout of its own metaverse, with mixed results. While some technologies filled a vital role in reconnecting the workforce, others were novelties at best and hindrances at worst. This article provides a candid review of the technical and policy elements that were explored as part of the Welcome to Our Metaverse experiment, the results that were observed, and the key takeaways and lessons learned for further exploration and technology adoption.**

***Index Terms*—Augmented reality, metaverse, mixed reality, spatial computing, virtual environment, virtual reality.**

I. Introduction

DRIVING up to the entrance of JPL in Pasadena, California, one is met by a large sign with the words, "Welcome to Our Universe." As a federally funded research and development center (FFRDC), JPL has been welcoming scientists, engineers and explorers young and old to experience the universe in a unique way that is hard to find anywhere else. For example, JPL operates NASA's Deep Space Network [1] used to communicate with spacecraft beyond Earth-orbiting missions, and JPL has landed and operated more missions on Mars than any other organization in the world [2]. JPL lives up to its motto to "Dare Mighty Things," and as the COVID-19 pandemic began in early 2020, JPL's Information and Technology Solutions Directorate (ITSD) applied that same spirit to investigate novel ways to address the challenges created by the new remote and hybrid work paradigm. Thus was born the "Welcome to Our Metaverse" project.

A key component to JPL's success has always been our ability to collaborate together in-person, whether on lab or at a favorite local cafe. When the COVID-19 pandemic hit in early 2020, we, like so many others, suddenly lost the option to be in close proximity to each other. We asked ourselves, how can we recapture those casual collaborative interactions that make up the "secret sauce" for our success? While traditional video-conferencing and asynchronous communication quickly became available for remote work setups, the constant barrage of back-to-back virtual meetings left many with "zoom fatigue" [3] and did not sufficiently facilitate the synergy that usually exists when people come together to solve meaningful problems. We knew we had to work around that "virtual meeting exhaustion" experience and find a way for people to engage in more effective ways. How could we recreate, via a virtual environment, the real-life experiences we had lost, such as water cooler conversations, productive and organic work meetings, and both large and small gatherings? Could we give people a sense of being "back at lab," even though they were working remotely from home? These were some of the questions that drove our research.

Since that time, JPL's Welcome to Our Metaverse project has explored metaverse-related technology as a possible solution to some of these questions. This paper explores what we tried, what we learned, and what we think the future of work might look like. As of this writing, the pandemic-related remote work restrictions have largely been removed; however, the paradigm shift is more permanent. There are still a large number of employees who continue to work fully or partially remote, and a hybrid work environment is still a daily reality. These questions are still very much important for the success of JPL.

The rest of the paper is organized as follows. First, in Section II, we review the relevant background of the metaverse in general, as well as how NASA and JPL have used metaverse-related technologies in recent years. Section III gives a detailed overview of the user experience needs, technology capabilities, and research methods that drove our project. Next, Section IV presents a deeper dive into several use cases we explored, which produced accompanying proof-of-concept experiences.

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Section V provides a discussion and review of lessons learned, followed by a brief conclusion in Section VI.

II. Background

The term "metaverse" is traditionally attributed to the 1992 novel *Snow Crash* by author Neal Stephenson, and it has been defined and thoroughly examined in various ways throughout the decades since then [4], [5], [6], [7], [8]. In the 2007 Metaverse Roadmap, Smart et al. wrote, "The Metaverse is the convergence of 1) virtually-enhanced physical reality and 2) physically persistent virtual space. It is a fusion of both, while allowing users to experience it as either" [4]. The Merriam-Webster dictionary defines it as, "a persistent virtual environment that allows access to and interoperability of multiple individual virtual realities" [9]. While many other definitions abound, it is generally understood that the metaverse includes a persistent virtual environment (typically a 3D virtual reality environment, but not necessarily [10]) and the ability for users to collaborate together in and interact with that environment. For our Welcome to Our Metaverse project, we used a similar definition and attempted to investigate any approaches that might bring value to the institution overall. Similar technologies and concepts related to the metaverse, but beyond discussing in the scope of this paper, include digital twins [11], mirror worlds [12], AR/VR [13], [14], [15], Computer-Supported Cooperative Work (CSCW) [16], [17], Immersive Analytics [18], Telelife [19], etc. With the sudden shift to remote and hybrid work brought on by the COVID-19 pandemic, interest in the metaverse skyrocketed, sparked in part by the desperate desire of companies and organizations to address this new problem of "Zoom fatigue" [3]. In 2021, Facebook became focused on leading the market to develop the metaverse, banking so much on this new wave to even rename itself "Meta." (Apple, on the other hand, has avoided the term altogether and had instead branded its foray into this field as "spatial computing" [20].)

In parallel with this renewed interest was a rapid innovation of both hardware and software in recent years, making metaverse technologies (i.e., headsets and applications) more accessible to consumers, not just big companies. For example, while previous head-mounted displays (HMDs) were too expensive and difficult to use for the average person (e.g., requiring external tracking hardware or instrumentation of the user's physical space), there are now numerous easy-to-use commodity devices available at the cost of an average smartphone. Examples include the Oculus (Meta) Quest [21], Tilt Five [22], Ray-Ban Stories smartglasses [23], and applications such as VR Chat [24], Spatial.io [25], and others. In June 2023, Apple also announced its Apple Vision Pro headset [20], again avoiding the use of the term "metaverse" but still clearly in the same category as the other examples mentioned. The popularization of the concept of the "metaverse" and the wider availability of software and hardware allowed many organizations, including JPL, to begin investigating in earnest how these technologies might shape the new hybrid work environment.

Previous research into the effectiveness of metaverse-related technologies (e.g., AR and VR) has shown strong potential of the technology in a variety of use cases [26]. This includes training [27], education [28], [29], data visualization [30], design review [31], meeting together [32], collaboration [33], [34], telepresence [35], etc. We encourage the reader to review prior surveys and reviews in this area for a more detailed understanding [5], [6], [8], [14], [15], [26], [36].

Finally, it is important to note that NASA, JPL, and Caltech had been investigating and utilizing metaverse-related technologies for several years prior to the pandemic (in addition to being early adopters of the technology decades before, such as with the Virtual Interface Environment Workstation [37]); here we mention a few examples:

- Ireton et al. utilized Second Life to create lunar exploration experiences [38], [39].
- OnSight is a collaborative augmented reality (AR) tool to allow scientists to explore 3D-reconstructed Mars terrain together [40], [41], utilizing a custom 3D terrain reconstruction pipeline [42]. In addition, efforts are underway to utilize the latest machine learning techniques to visualize Mars terrain [43].
- Utilizing HMDs for spacecraft inspection tasks [44] and augmented reality for International Space Station (ISS) maintenance [45].
- ProtoSpace is a collaborative AR tool for helping engineers design, assemble, and maintain spacecraft and instruments [46], [47], [48], [49]; in this paper, we describe some preliminary efforts to port ProtoSpace to virtual reality (VR) (see Section IV-E).
- Utilizing AR and VR for data visualization [50], including for earth science [51].
- The Cold Atom Lab utilized live remote collaboration with an astronaut wearing a HoloLens AR headset aboard the ISS for remotely-guided science instrument maintenance [52].
- Tate et al. is investigating the use of Mozilla Hubs [53] for collaborative viewing of reconstructed Mars terrain [54].
- NASA's CHAPEA mission has been utilizing virtual reality for simulating walking outside of a Mars habitat [55], [56].

III. Welcome to Our Metaverse

In this section, we give a brief overview of our approach to investigating metaverse technologies. This includes user experience (UX) considerations (Section III-A), technical considerations (Section III-B), our initial evaluation of various commercial-off-the-shelf (COTS) applications (Section III-C), a list of hardware used in the project (Section III-D), and finally our approach to 3D capture (Section III-E).

Please note that throughout this entire paper reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

A. User Experience (UX) Considerations

Our first step was to consider and identify the UX requirements for a JPL metaverse experience, including specific requirements as well as broad heuristics [57], [58]. Our priorities were:

1) *Ease of Use/Usability:* As with any digital application, the usability of the system is of utmost importance. Particularly for metaverse-related technologies that run on immersive platforms, the requirement for ease of use is arguably higher than with traditional platforms (e.g., desktop, mobile, tablet); end-users may need to adjust to both the platform as well as the application. If the value-add is outweighed by poor usability, then there is less reason to adopt the system.
2) *Accessibility:* Another key aspect that we considered was accessibility and how well the platform addressed the full spectrum of use cases, ranging from all employees fully remote to mostly in-person with a few remote users. This was important because this is where most video conference platforms struggle, with remote attendees receiving a lower quality experience than in-person attendees.
3) *User Journey/Onboarding:* Arguably a subcategory of the previous two items, the user journey refers to how users onboard into the experience. For example, some applications require multi-step user account and profile creation, whereas others do not, and some applications' avatar creation may take longer than others. If a technology takes too long to get into the experience or learn how to use it, then again the value-add may not outweigh the burden.
4) *Ergonomics/Comfort:* Unlike traditional 2D-screen platforms, the physical experience of an immersive platform plays a much bigger role in how engaged a user is and how effective the platform is. Aspects such as weight, comfort, and battery life can all affect the user experience. We chose to explore several different headsets (see Section III-D) and evaluated them on visual quality and high enough fidelity to actively immerse users into the virtual environment. Additionally, the user must be able to comfortably wear or interact with the device for an extended amount of time, for example an hour-long meeting, or even multiple meetings. Finally, after long sessions, users must be able to comfortably transition from the virtual space back to their physical space.
5) *Spatial Audio:* When supporting a large virtual meeting, it is important to have the ability to both hear people and not hear people. Just like a physical meeting, we want the ability for one person to address all other meeting participants as well as the ability for small, quiet conversations to occur between only a few people.
6) *Ability to Express Yourself:* In a physical meeting, people are able to express themselves with both speech and body language. In a virtual platform, we want similar expression as well as types of expressions that don't exist in the physical world (e.g., emoji reactions). Ideally users can have a large range of expression; however, as with any application, more features tend to risk a reduction in usability.
7) *"Uncanny Valley":* One unique aspect of evaluating virtual and immersive platforms is need to address the uncanny valley phenomenon [59], [60], [61]. There are some indications that the "uncanny valley" effect is stronger when using a VR headset than a 2D monitor [61]. Some platforms try to avoid this issue by using "cartoonish" avatars, while other platforms do their best to create avatars as photorealistic as possible while aceepting the risk of viewing and interacting with those avatars causing uneasiness for some people.
8) *Support of Specific Meeting Types:* There are many different types of meetings, each with their own specific set of UX and technical features that are important to have. A preliminary survey of those meeting types and important features is summarized in Table I, including a ranking of the top three VR applications that we determined were most applicable to each meeting type.

B. Technical Considerations

In addition to the aforementioned UX considerations, we also outlined the following technical requirements:

- Most important ("must have") features:
  - For VR applications, compatibility with Meta Quest 2—due to its popularity, price, and reliability, we chose the Quest 2 as our main headset for our investigation.
  - Built-in voice-over-IP (VOIP)—voice communication is essential for live, synchronous collaboration. Note that we did not focus on any asynchronous collaboration tasks where having other forms of communication might be additionally desired.
  - More than 16 simultaneous users—we wanted to support medium to large meetings.
  - US Company—for cybersecurity reasons, we chose to only use US-owned platforms for any proof-of-concept prototypes.
- "Nice-to-have" features:
  - Custom environments—while not a required feature, the ability to import 3D scans of a physical space was an extremely important use case for our project.
  - Browser support—allowing users to access the platform via both a VR headset as well as a traditional web browser would further support accessibility UX considerations as well as allow for a broader set of JPL employees to experience the metaverse if they are unable or unwilling to use a VR headset.
  - Avatars—due to the spatial nature of metaverse platforms, having a virtual representation of one's self, in the form of an avatar, is an extremely useful feature to have.
  - Webcam support—while avatars are a definitive part of the metaverse experience, the ability to show one's face via a webcam was a nice-to-have feature.
  - Screen sharing/broadcast—many work meeting tasks involve sharing a computer screen; if that is not available, some platforms may have the ability to upload a PDF or slide presentation instead.
  - WebEx integration—at the beginning of the project, JPL mainly utilized the WebEx video conferencing

TABLE I
LIST OF MEETING TYPES CONSIDERED WHEN EVALUATING VARIOUS VR APPLICATIONS

Meeting Type	Description	Important Features	Who's Talking?	Sharing Screen?
All-hands	One or more people speaking to a large audience with an accompanying presentation; typically with questions allowed at the end	Browser support for hybrid WebEx, share screen	Mainly speakers	Usually
Working Meetings	Communicate and work together to solve a problem; usually multiple apps involved	Access to computer	Everyone	Sometimes
Standup Meetings	Used for communicating updates with your team	Low barrier to entry; browser support	Everyone	Sometimes
Trainings	One presenter, but have breakout groups to understand a concept	Breakout room functionality or spatial zones	Mainly speakers	Sometimes
Networking / Conference Meeting	Have one presenter but also allow others to communicate and network before and after the meeting	Many people, browser support, share screen	Everyone	Maybe
Happy Hour	Casual, small group chatter about work and non-work topics	Activities; audio attenuation	Everyone	Rarely
Lab Training	Training someone to use a physical lab but virtually/remotely	Support for accurate 3D scans; importing 3D models of tools	Everyone	Rarely
Unconference	Open with plenary discussion/agenda planning - then lots of little breakouts with people having freedom to move between them	Whiteboard, audio attenuation, breakout rooms or spatial zones	Everyone	Rarely
Pair Programming	1:1 programming	Good share screen and access to computer	Two people	Yes
Poster Event	Walk around and talk about each other's posters	Ability to share presentations / PDFs; large number of people	Everyone	Rarely
Coffee Buddies Meeting	1:1 or small group meeting where your intention is networking and getting to know each other.	Avatars, video	2+ people	Rarely

application [62]. While ideally all meeting participants used the same platform, we recognized that some users were not ready to jump into a metaverse platform just yet but still wanted or needed to participate in a hybrid meeting (see Section IV-A).
– Collaboration features—this includes features such as chat, a virtual whiteboard, the ability for users to add content into the virtual space, etc.

Fig. 1. 3D scan of a conference room inside a metaverse application, showcasing the ability to provide users with a sense of being back at the office.

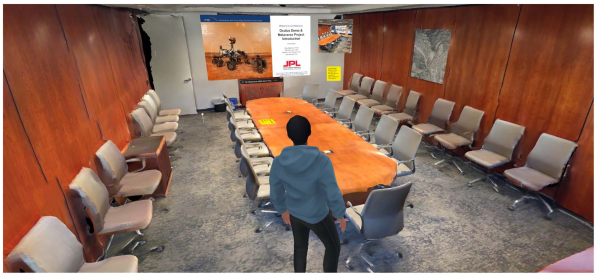
C. Initial Software Evaluation

We began the initial evaluation and testing of VR metaverse applications in the Fall of 2021. The initial applications included: Spatial [25], Mozilla Hubs [53], Facebook Horizon Workrooms (now called Meta Workrooms) [63], VRChat [24], AltspaceVR [64], Immersed [65], vSpatial [66], Glue [67], MeetinVR [68], Frame [69], and BigScreen [70]. Various members of our division were also simultaneously testing the non-VR application Gather Town. Based on the initial set of UX and technical requirements (Sections III-A and III-B), we determined that the systems which came closest to our list of requirements at the time were Gather Town, Spatial.io, Mozilla Hubs, and Horizon Workrooms.

Gather Town is top-down 2D spatial interface for collaborative experiences (see Figs. 5, 6, and 12) and will be discussed in detail later on (see Sections IV-A–IV-C, and V). While not a VR application, overall the platform still does a good job of facilitating similar to real-life interactions in a fully virtual space. It also is browser based so it is more accessible and inclusive.

Spatial (see Figs. 2 and 3; discussed in greater detail in Sections IV-A, IV-C, IV-D, IV-G, and V), allowed us to import LIDAR scans made from iPhones and iPads which allowed users to enter a virtual representation of real lab spaces and interact with those spaces. This allowed users to experience the physical space of Lab despite never having been in-person (e.g., new hires during the pandemic). Spatial also had the feature of semi-photorealistic avatars, which appealed to many people since it made it easier to quickly recognize others in the virtual space.

Hubs supported 3D scans at a slightly higher resolution, but in limited capacity. The memory caps prevented large high resolution scans from being imported, but because it is open source teams could theoretically host their own instances with more capacity. One appealing feature of Hubs was that it was very easy to join (no user account creation required; no apps to download). However, due to some issues with spatial audio falloff and poor screen sharing resolution, we ended up not using Hubs as much as the other platforms and instead only tested with it early on. However, others in the JPL community have since used



(a) 3D scanned conference room where the chairs around the table were digitally copied and pasted from a single high-quality chair scan.

(b) Viewing the captured photosphere skybox through the window.

(c) Zoomed out view, showing the captured photosphere skybox around the 3D model.

Fig. 2. Variety of views of a 3D scanned conference room with a captured photosphere used as a skybox to show the view out through the window of the conference room.

Hubs for VR collaborative viewing of 3D reconstructed Mars terrain [54].

Finally, Horizon Workrooms (see Fig. 8; discussed in greater detail in Sections IV-A, IV-C) also met our requirements. While Workrooms is a VR application, users are not free to fully move around in the virtual environment but are instead constrained to specific areas (e.g., chairs, whiteboard). Unlike Spatial, Workrooms does not attempt to use photorealistic avatars and also doesn't allow non-humanoid avatars (unlike Hubs or VRChat). Non-VR participants do not have avatars but instead show up on a virtual big screen monitor, mimicking a real hybrid meeting.

D. Hardware

We tested and used the following hardware as part of this project:

- Quest 2—for most VR applications. As mentioned in Section III-B, we chose the Quest 2 due to its popularity, price point, and overall reliability.
- Quest Pro—for some VR applications. Some users reported that the Quest Pro gave them more eye fatigue compared to Quest 2 and HoloLens headsets.
- HoloLens 2—for hybrid AR/VR (Section IV-G) and for CAD visualization (Section IV-E).

Fig. 3. JPL's first division all-hands meeting in a 3D metaverse environment; here, users joined the virtual environment with semi-photorealistic avatars and were able to spatially explore the space together and have small-group conversations.

- Tilt 5—for viewing Mars rocks in a metaverse. We did preliminary tests with the Tilt Five AR gaming board to see if it could be used for viewing Mars rocks in AR. The system's integration with SketchFab [71] allowed for easy importation of Martian terrain that has been 3D reconstructed by the science community [54]. However, it was not very easy to achieve proper real-world scaling and alignment with the physical world.
- Canon R5 Camera with Dual Fisheye Lens—for virtual lab tours (Section IV-D) and mission operations training (Section IV-F).
- Leica BLK360—for 3D scanning (Section III-E)
- iPhone (11 Pro Max, 13, and 14 Pro Max)—for 3D scanning (Section III-E)
- iPad Pro, 5th generation—for 3D scanning (Section III-E)
- Google Pixel 3a—for photospheres used in conjunction with 3D scanning (see Fig. 2(c) and Section III-E).

E. 3D Capture Technologies

While some might think of the metaverse as being a purely computer generated environment, we saw an opportunity to use 3D capture technology to recreate the real JPL campus, giving remote workers a sense of being at the lab and a feeling of "presence" [72], [73].

While there are a variety of approaches for reconstructing and rendering the 3D visual reality of physical spaces (e.g., see the entire image-based rendering spectrum of possible techniques [74]), the most popular techniques involve either some form of photogrammetry or LIDAR scanning. We tested traditional photogrammetry approaches–using Agisoft Metashape and Alicevision Meshroom [75], [76]—but we quickly came to the conclusion that these approaches are not ideal for indoor spaces, mostly due to the homogeneous visual texture prevalent in office spaces which hinder purely visual approaches. We also tested dedicated LIDAR scanning with a Leica BLK360 scanner and found that while it had higher accuracy (especially for indoor spaces), the resulting scans were not immediately ready for use in COTS VR software due to the enormous amount of data in each scan (e.g., millions of points in the point cloud). The LIDAR output was also a 3D point cloud, which is arguably less appealing than a fully textured 3D mesh.

LIDAR scanning apps on iOS mobile devices (e.g., iPads or iPhones) ended up being the most accessible option. We tested several COTS apps, including Polycam, 3D Scanner App, SiteScape, Scaniverse, and more. In the end, we used Polycam for most locations. Scanning a typical conference room or small office space took as little as 10 minutes and in most instances, the resulting scans were ready to use without any post processing. In some cases, some physical objects such as office chairs were difficult to scan; for these we experimented with either reading in CAD models of those objects or doing one high-quality scan of that object and digitally copying and pasting it to the room scan; Fig. 2(a) shows one example. In addition, we also experimented with capturing a skybox of a location using the Google Pixel 3a's camera's "photosphere" mode; this was particularly helpful for showing outside a window of a conference room, as shown in Fig. 2(b) and (c). If post-processing of a scan was required, we typically resorted to manual clean up of the scan using Blender [77]; however, other tools are available such as Pixyz [78] and MeshLab [79]. To facilitate experiencing different scans, we added "portals" in the Spatial platform to allow users to teleport between the different scans; a similar approach was also done by Tate et al. in Mozilla Hubs [54].

The team also explored capturing immersive experiences with a Canon Dual Fisheye lens [80]. Having the ability to shoot high resolution native stereo video is extremely useful; however, the wide field of view of the lens dictates how to film things. For example, the wide angle lens is great for small detailed subjects, but falls short when trying to capture longer broader shots. We also experimented with live-streaming from the lens and novel ways to view the stereo footage for virtual tours (see Section IV-D), as well as capturing footage for technical training for mission operations (see Section IV-F). In the latter case, an example question is, does capturing the experiential aspect of a human-to-human interaction facilitate comprehension of the tasks?

Finally, we should note that there are some newer techniques that are gaining popularity but did not make it into our analysis. First, with the advent of modern cloud computing and edge computing, remote rendering is becoming a viable option for many applications. Remote rendering allows high-resolution and interactive immersive content to be streamed to a user's device in real time. As of this writing, there are numerous commercially available solutions, including Microsoft Azure Remote Rendering [81], Google Immersive Stream for XR [82], NVIDIA CloudXR SDK [83], and others. Second, a class of rendering algorithms called Neural Radiance Fields (NeRF) [84] have recently exploded in the research community, even being applied to Mars terrain [43]. Typically NeRF approaches require more processing power to both build and render these 3D models of physical reality; however, active research is being done to apply them to real-time use cases, including for VR [85]. Our project spent a brief time experimenting with freely available tools including Luma AI [86] and nerfstudio [87].

IV. Case Studies

In this section, we go into more specific details of the use cases we explored.

A. Division All-Hands Meetings

In November 2021, JPL's AI, Analytics and Innovation Development division began experimenting with holding division all-hands meetings in various metaverse platforms, to test out the experience in a practical and real-world setting. Platforms included Spatial, NOWHERE [88], Gather.Town, and Meta Workrooms. For the all-hands meetings, we opened the virtual meeting room approximately 30 minutes before the scheduled meetings to allow users to join earlier to get acquainted with the platform and to troubleshoot any technical difficulties. Further, we provided set up guides for users to create their avatars and get acquainted with the Spatial system.

As shown in Fig. 3, our first division all-hands meeting in the metaverse was conducted in a computer-generated campfire environment within the Spatial.io platform. Having semi-photorealistic avatar faces allowed participants to quickly recognize others in Spatial. The campfire environment was large enough to let users explore the space, test out the features of the platform, and hold 1-on-1 or small group conversations. A slideshow was also presented from inside the virtual environment. Roughly half of the Spatial users joined via a VR headset, while the other half joined via a web browser. Since the participant limit for Spatial was capped at 32 people, we also set up a hybrid meeting with WebEx to allow for more participants. This was accomplished by sharing a WebEx browser tab (with its audio) into Spatial—so that the Spatial meeting participants could see and hear WebEx meeting participants—and by sharing the Spatial browser tab via a "virtual audio cable" and "virtual camera" [89] as a participant in WebEx—so that WebEx participants could see and hear Spatial. Allowing additional participants to join via WebEx was a successful way to give all employees a taste of the metaverse regardless of platform familiarity.

Another all-hands meeting was also conducted in Spatial using a custom 3D-scanned environment of the division's dedicated space on lab; see Fig. 4. For many participants, this was the first time they had seen the lab space since the COVID lockdown began. For those hired during COVID, this was their first view of the lab space ever. A similar setup utilizing WebEx was used to allow employees the option to participate without entering the metaverse environment. Division leadership as well as employees shared presentations about work completed over the last month. Now that there was added familiarity with the system, there was more nuanced views about the overall experience. An overall sense of presence was noted alongside a rising sense of uncanny valley due to the semi-photorealistic avatars. The decision was made to try other applications in future all-hands.

We tested an all-hands meeting in a Gather.Town space that was representative of the same physical meeting space owned by

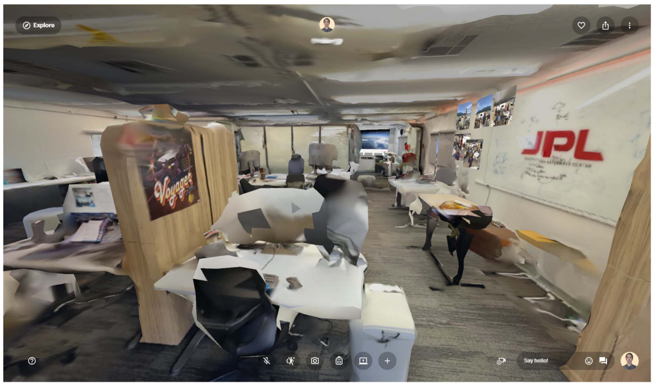


Fig. 4. 3D-scanned office space that was used for a division all-hands meeting. Note that this space was owned by the same division and thus gave meeting participants a sense of being back at the office, which is important for current hybrid and remote work situations.

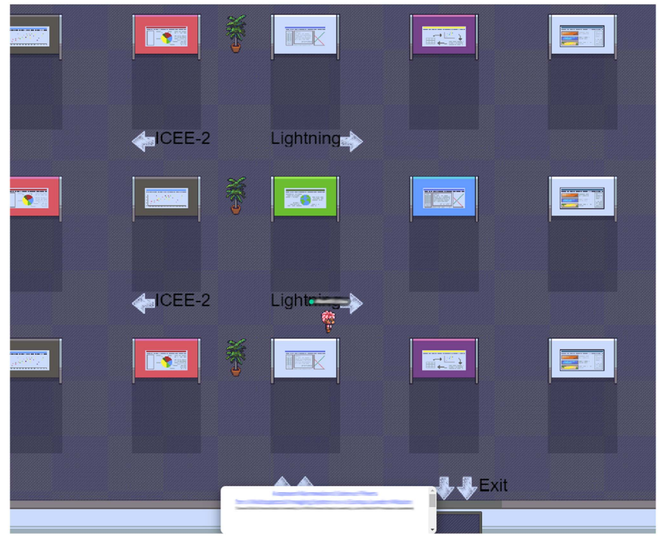


Fig. 5. Icy Worlds Poster Session in Gather.town. Just as in a real-life poster session, authors could stand (virtually) in front of their posters and engage in meaningful conversations with other people.

the division, with the addition of a large meeting hall. Similarly to Spatial, Gather.Town allowed for small 1-on-1 or small group conversations via a spatial audio falloff feature. Additionally, Gather.Town has a spotlight tile feature that allows participants standing on a special tile to project their voice to the whole environment, overriding the spatial audio falloff distance. This was particularly useful during the all hands for presentations as it was a part of the virtual environment versus the toggle-able setting in Spatial. One issue that came up was that doorways were often tricky to navigate, since the avatars have impassable bounding boxes. Furthermore, the bounding boxes and the spatial audio falloff made it such that larger group conversations were not possible due to too many people occupying the audio falloff space. There were no reported feelings of uncanny valley, likely due to the 8-bit customizable avatars.

Finally, we also tested an all-hands meeting in Meta Workrooms and NOWHERE. Meta Workrooms allowed for selected presenters to talk to a larger audience that was not in the virtual space. This is also a downside of the platform in that it does not allow everyone the same virtual presence, and leaves the majority of users in a state where they can watch and listen, but not really participate. NOWHERE is unique in that the platform has users show up as abstract circulars that shows their video feed, which worked when users were face to face, but became unsettling if you were behind another user or looking at them from the side. Additionally, NOWHERE lacked some of the technical needs of our team, such as adequate spatial audio falloff and audio projection.

With the exception of Meta Workrooms, many participants reported feeling that, compared to traditional video conferencing platforms, they could more easily hold small conversations and avoid having one person dominate the meeting. Having a *spatial* interface that allowed for a closer to real-life experience was generally seen as very useful—some users reported actually talking to other coworkers for the first time ever. Based on the feedback, the all-hands meeting experiments in these various metaverse platforms were generally judged a success.

However, a number of issues were also reported over the course of our testing. First, not everyone in the division had a VR headset—only a limited number had access to a headset or were interested in trying one. In the hybrid WebEx/Spatial instance, those who joined via WebEx were very much on the sidelines and had very little presence in the experience; those in Spatial (using web browser or VR headset) could spatially move around the virtual environment and thus had a much more interactive experience and most reported feeling part of the meeting. One user who joined Spatial with a HoloLens headset reported being stuck in the middle of the space and was not able to navigate elsewhere (Spatial has since dropped support for HoloLens).

Perhaps the biggest user experience obstacle was that all platforms consistently ran into various technical issues. For example, users wearing VR headsets would often have poor network connectivity and drop in and out of the meeting. Some users joining from a web browser had trouble getting into the meeting platforms, either due to usability issues or network connectivity issues. A few employees opted to skip the all-hands meetings entirely since they saw it as too difficult to participate in it. Several users indicated that for important meetings they preferred to stay on more traditional video conferencing platforms due to their reliability. Finally, some users reported being constantly distracted by the avatars, either by their appearance (see Section V-A) or their movements (e.g., hands moving in weird positions due to users' VR controllers being placed down). These and other issues prompted us to decide that the platforms were not yet mature enough for widespread adoption and regular use.

B. Poster Events

Gather.town was used for a poster event at the Icy Worlds Workshop. This was set up as a virtual version of JPL's in-person poster events (see Figs. 5 and 6). The Gather.town space hosted about 75 people and, 2D graphics aside, was a close approximation to the experience of walking around and mingling at an

Fig. 6. Icy Worlds workshop in Gather.town. Just as in a real-life workshop, participants could gather in small groups. Unlike traditional video conferencing, 2D spatial interfaces provide an arguably more intuitive approach for quickly seeing and choosing which group discussion one would like to join.

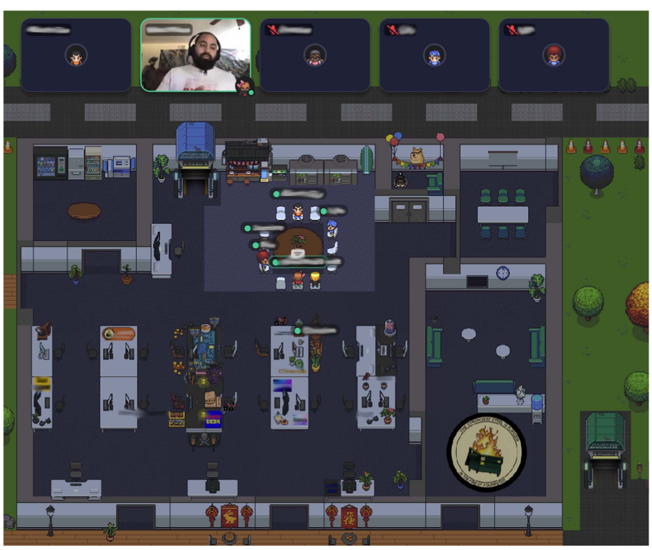


Fig. 7. Small group meeting in Gather.town. This space was replicating the same physical space that was scanned in Fig. 4.

in-person poster event, more so than using traditional meeting software like WebEx or Zoom. One of the lessons learned was that even a virtual space can be too big, and it took a long time for people to move through the different areas. Room layout also appears to be key even in a virtual space, and in the future we might engage the expertise of conference layout designers.

C. Smaller Meetings

We tested a variety of applications for small group meetings with less than 10 people (e.g., see Fig. 8). These meetings were either "standup" meetings, focused on communicating updates to all team members, or "working" meetings, focused on working together to solve a problem (see Table I). In the end, we mostly resorted to using Gather.Town and Spatial, with the former being used when we needed high accessibility and the latter being used when we needed to support custom 3D-scanned environments.

Fig. 8. Testing out Workrooms for a small group meeting. Unlike other applications that allow you to wander freely through the virtual environment, Workrooms constrained participants' locations to predefined areas, such as the four chairs in this instance.

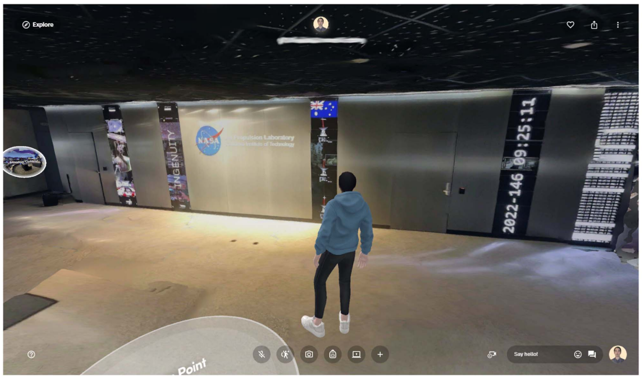
D. Tours

We also tested various approaches for virtual tours of JPL for both remote employees and the public. Public tours of JPL were temporarily ceased during the Covid-19 pandemic, and meanwhile JPL had an influx of new hires who could not come on lab for their customary orientation. Thus, we also explored whether metaverse-related technologies could give people the experience of physically visiting and exploring JPL. We first reviewed the existing JPL Virtual Tour website [90], which recently won a People's Voice Webby Award in 2022 [91], to further understand what has already been done and where there may be potential gaps. We then identified several potential areas of technology infusion for further prototyping.

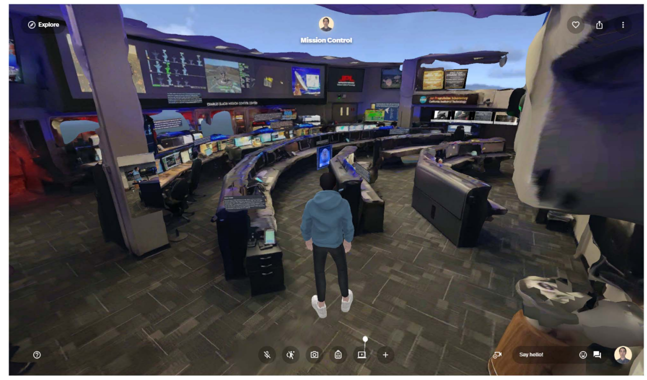
First, we experimented with creating 3D scans of the locations currently on the JPL Virtual Tour. We utilized Polycam LIDAR scans and imported these into Spatial.io. See Fig. 9. However, the fidelity of LIDAR scans was not detailed enough to create the experience we had hoped for. Future work might be able to leverage NeRF technology for higher fidelity 3D scans.

We also experimented with immersive camera technology. After reviewing several VR camera choices, we decided to try the Canon Dual Fisheye Lens attached to a Canon R5 camera. While LIDAR scans provide the ability to let the VR user move in 6-degrees-of-freedom, they also provide lower fidelity overall. VR cameras, on the other hand, typically force the user to see the scene from one perspective but maintain a high resolution capture from that one perspective. We experimented with both recording VR180 stills and videos which could then be viewed using Google Cardboard-style smartphone viewers or VR180 viewing apps with the Quest 2 or Quest Pro headset.

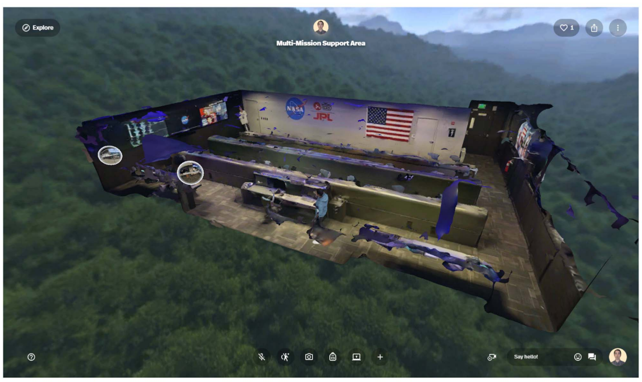
In October 2022, we conducted the first-ever VR180 livestream tour to internal JPL employees (see Fig. 10). We set up the Canon R5 + Dual Fisheye Lens attached to a laptop



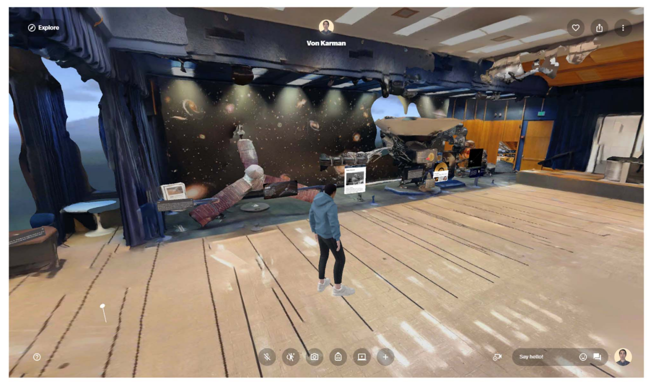
(a) Mission Control Lobby. Here, the flat walls made it easier to get a good-looking scan due to the simplicity of the geometry.



(b) The Mission Control Room is still used today for Deep Space Network [1] operations and is a limited public tour location.



(c) The Multi-Mission Support Area is more broadly used for the most recent flight mission operations, including the landing of Mars rovers.



(d) Von Karmen Auditorium contains physical scale models of spacecraft which were hard for our LIDAR scanner to pick up in good detail.

(e) The Visitor Center Museum had many intricate details that were extremely difficult for our smartphone LIDAR scanner to capture, resulting in a very messy looking scan.

Fig. 9. Sample of 3D scans utilized for virtual tours. In some instance, the scans had fairly good-looking results, while in other cases the scans resulted in messy-looking scenes. See Section IV-D for more details.

which streamed the video over WebEx while a tour guide connected to WebEx with their smartphone to provide audio narration. Remote users could view the VR180 live stream with a Google Cardboard-style smartphone viewer. The laptop received the VR180 dual fisheye distorted video and converted it to an equirectangular projection [93] in real-time using a custom shader for OBS Studio [89]. Fig. 11 shows an example of the effect of the shader.

We also experimented with creating a custom VR180 WebXR viewer that allows users to see multiple VR180 photos taken from a similar location but with different views of the space. We mounted the VR180 camera on a tripod and took several photos, rotating through 360 degrees. This was typically around 12 photos, each separated by approximately 30 degrees. Next, a more accurate relative rotation offset was approximated using OpenCV's implementation of Enhanced Correlation Coefficient

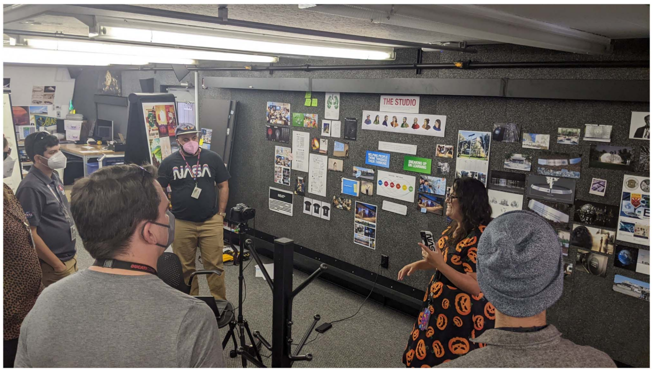


Fig. 10. First VR180 live-stream conducted at JPL, touring The Studio [92]. Note the Canon Dual Fisheye Lens on the tripod in the center of the room that was used for live-streaming.

Maximization [94]. We then ingested the VR180 photos and the calculated rotational offsets into a WebXR app. Based on which direction the user's headset is viewing, we can toggle which VR180 photo should be shown to the user. This allowed the field of view to be extended from only 180 degrees to a full 360 degrees. Moreover, unlike traditional 360 photography which has either no stereoscopy available or a stereo that is stitched together from multiple cameras in a VR360 camera, this approach allowed us to utilize the direct VR180 photos for each viewing angle without any stitching or machine learning applied to estimate scene depth. Future work with the VR180 approach could use machine learning approaches to estimate a depth map of the scene to enable 6-DoF movement [95].

Finally, we tested using Gather.Town for tours; see Fig. 12. Public tour locations, such as the Von Karman auditorium, the outdoor "Mall" area, and the mission control center were recreated in the virtual space. While Gather.Town cannot support an exact 1-1 spatial replication of a physical space, it does allow one to still have some spatial layout resembling a physical space, which for one user helped them navigate a part of Lab they had never physically been to before. In addition, Gather.Town provides the ability to link to external content, allowing us to reuse existing tour material.

E. CAD Visualization

Mixed-reality technology has advanced collaboration, work processes, and complex information visualization across industries. ProtoSpace, a software package developed by JPL, utilizes mixed-reality platforms to revolutionize collaborative visualization of mechanical CAD models [46], [47], [48], [49]. See Fig. 13.

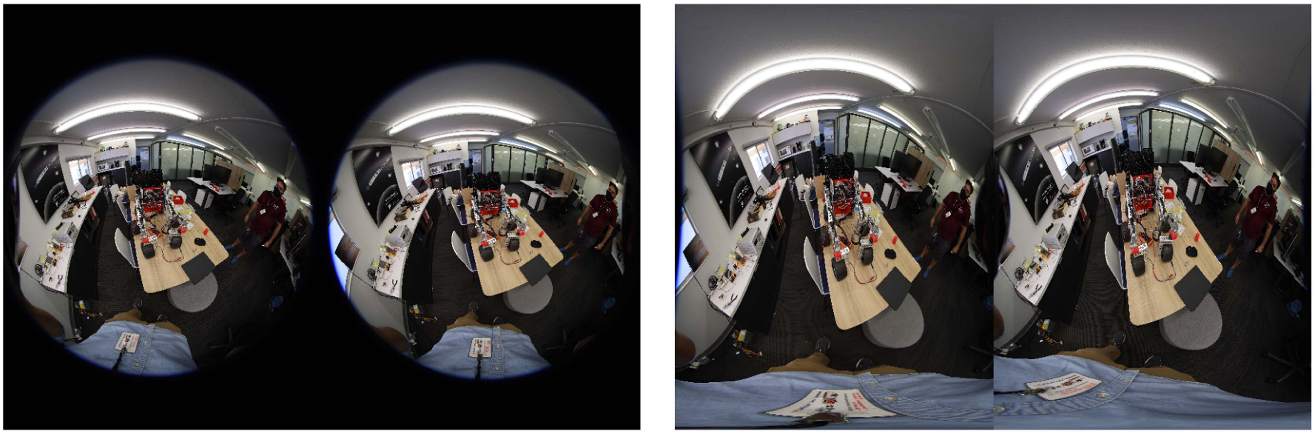
Using the Microsoft HoloLens, ProtoSpace allows users to interact with and explore 3D CAD models, facilitating early issue identification and reducing project costs and risks. While most of the Welcome to Our Metaverse project focused on applying Metaverse technology to the broader use case of remote and hybrid meetings in general, ProtoSpace was one particular instance of upgrading existing JPL software to utilize the latest technology.

To further enhance ProtoSpace, the software was ported from AR on the HoloLens to VR on the Meta Quest 2. More specifically, the process involved improving text visualization, implementing hand tracking for intuitive interactions, and enhancing visual fidelity with VR environment elements. The porting of ProtoSpace to VR demonstrates the benefits of leveraging a variety of technologies, such as VR, to enhance the overall collaboration experience. The techniques used in this process have broader applications for usability and impact in other VR applications, including the emerging metaverse.

Improving the UI text quality was one of the key aspects of porting ProtoSpace to VR. The text displayed in the application had a shimmering effect at further distances, causing readability issues. Research revealed that the problem was attributed to texture aliasing, a common challenge in extended reality (XR) development [96]. To address this, various anti-aliasing techniques were investigated. Multisample Anti-Aliasing (MSAA) was considered, but since the project already utilized 4x MSAA, further multisampling would have had minimal quality improvements [97]. Another potential solution explored was integrating the Mixed Reality Toolkit (MRTK), a cross-platform toolkit for VR and AR app development [98]. However, the MRTK did not offer a suitable remedy for the root cause of the blurry text issue. Ultimately, TextMech Pro (TMP) was chosen as the solution. TMP is a popular replacement for Unity's default text components that employs Signed Distance Field rendering, enabling crisp text rendering regardless of size, resolution, or distance from the camera [99]. In contrast, Unity's default UI text employs bitmap fonts that can appear fuzzy at certain distances. To implement this solution, the primary UI text component in the project was switched from the Unity default to TMP. This involved importing the TMP namespace (named TMPro) into the program scripts that utilize text and updating all text objects in the project to utilize TMP.

The Quest utilizes a tracking feature to monitor hand position and orientation, contributing to the development of immersive experiences in the emerging metaverse [100]. With its infrared cameras, it captures real-time hand movements, enabling the detection of complex gestures. To enable this functionality in ProtoSpace, the Oculus Interaction SDK was incorporated to create a robust hand gesture detection system. Predefined gestures like pinch, grab, poke, and release were used to manipulate the toolbox. See Fig. 14.

Creating custom hand gestures involved understanding the hand tracking system's architecture and data, designing tailored gestures for ProtoSpace's toolbox, and defining finger positions called finger features. Hand poses are formed by shapes and transformations [100]. Testing was conducted in a separate Unity project to experiment with timing, spatial awareness, and hand models. After defining the gestures, they were implemented using a script that detects and triggers corresponding toolbox features. The user's hand positions and orientations were mapped to recognize gestures, and precise timing considerations were made. Interaction with the toolbox was enabled through the gaze cursor and air tap gesture (to keep interface style similar to the existing approach for HoloLens), facilitating intuitive control within the environment. Creating custom hand gestures was a



(a) Raw, distorted image from the dual fisheye lens

(b) Equirectangular projected image used in live-streaming

Fig. 11. Example of conversion from dual fisheye distorted to stereo equirectangular projected. As discussed in Section IV-D, we implemented a custom shader for OBS [89] to do this in real-time for the first-ever VR180 live-stream conducted at JPL as shown in Fig. 10.

Fig. 12. Gather.Town recreation of JPL's outdoor "Mall" area that was used for virtual tours; see Section IV-D for more details.

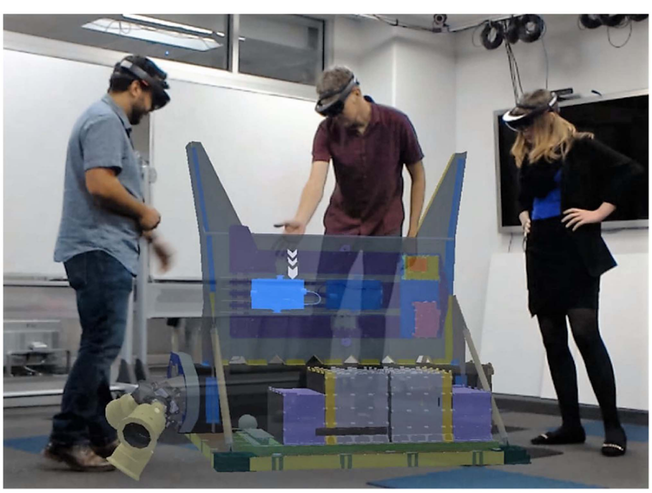


Fig. 13. Engineers at JPL check the design of a spacecraft assembly using ProtoSpace on the Microsoft HoloLens.

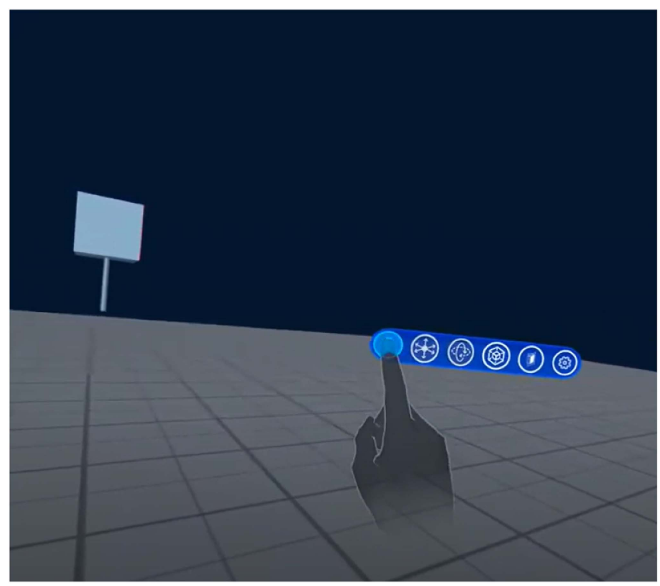
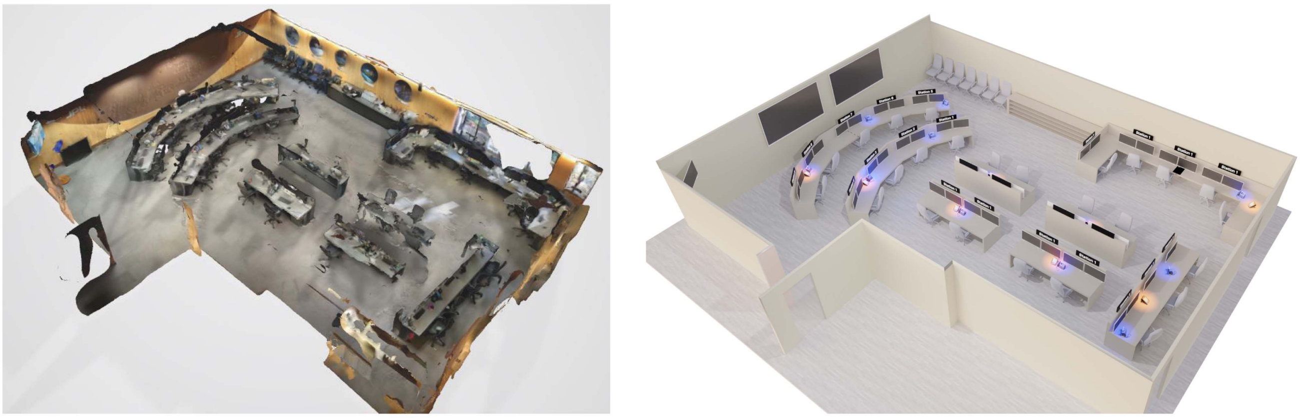


Fig. 14. Using the poke gesture to interact with the ProtoSpace toolbox menu in VR. While traditionally, ProtoSpace is used in augmented reality, the Welcome to Our Metaverse project began porting it to VR.

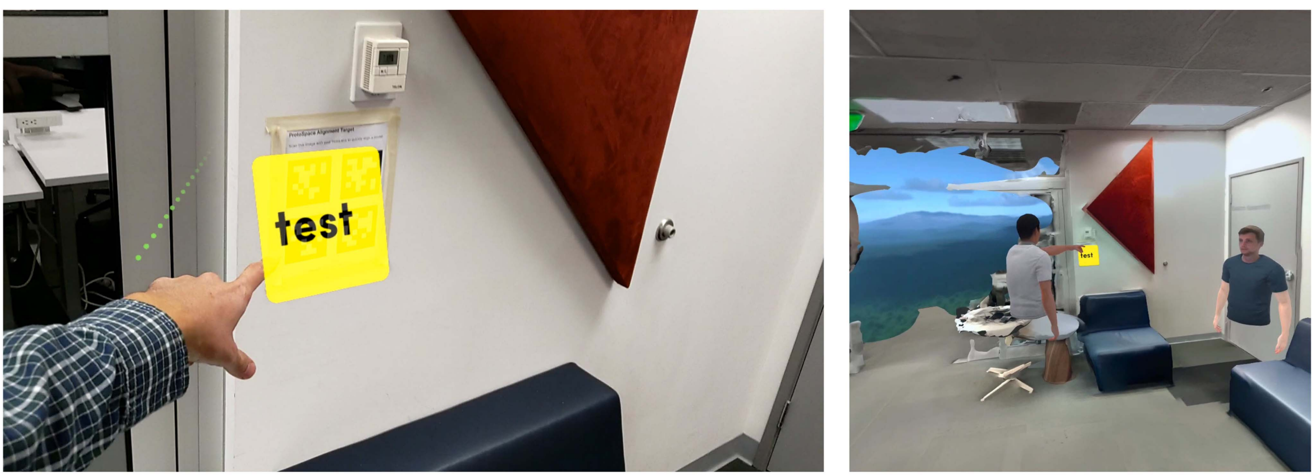
challenging process, particularly due to limited documentation and support. However, it was a crucial step in fully leveraging the capabilities of the Oculus Quest hand tracking system, providing users with a more natural and immersive way to interact within the metaverse. The integration of custom hand gestures significantly enhanced the user experience, reducing the learning curve associated with traditional interfaces and fostering collaborative engagement within the application. Despite the challenges encountered, this endeavor exemplifies the potential of the Quest hand tracking system in shaping innovative applications for the metaverse.

In addition to advancing hand gesture detection capabilities, some emphasis was placed on elevating ProtoSpace's immersive experience. By integrating VR environment elements such as a floor plane and skybox, ProtoSpace achieves a more realistic and immersive experience for users. The custom shader for the floor plane, with its realistic textures, reflections, and radial fade, contributes to the spatial perception and sense of presence within the virtual environment. The inclusion of a subtle grid pattern



(a) 3D scan of the mission operations environment. (b) Low-polygon representation of the same mission operations environment.

Fig. 15. For the mission operations use case (Section IV-F), the low-fidelity of a 3D scan (left) may be more distracting than a low-polygon representation of the same space (right), since users are mainly interested in understanding the spatial layout for functional tasks.



(a) View from HoloLens, in augmented reality, showing a virtual annotation. (b) View from Quest 2, in virtual reality, showing both a 3D scan of the physical space as well as avatars of users.

Fig. 16. Example of Hybrid AR/VR Remote Collaboration (Section IV-G). Note the location of the "test" note being properly aligned in both the physical space and the 3D scanned space; also note the synchronization of the user's hand pointing in real-life as well as in the VR scene represented by the avatar hand.

aids in depth perception and user orientation. The integration of these elements not only enhances ProtoSpace's visual fidelity but also demonstrates the potential of the metaverse to provide immersive and visually engaging collaborative environments for complex engineering projects.

F. Mission Operations

For mission operations training, it is important for people to understand not only the detailed technical knowledge of their assigned roles but also the spatial layout of the room and location of the related operational roles. To facilitate a mission operations training in the metaverse, we 3D-scanned and created Dual Fisheye recordings of existing mission operation spaces. Through interviews with mission operators we found that the layout of the mission operations environment is more important than having highly detailed 3D scans. This was in part due to the low fidelity and distracting nature of components of the resulting scans, for example, monitors and chairs. Mission operators preferred to utilize a low-polygon representation of the room so as to maintain focus on the training. The difference of the 3D scan and the low-poly representation may be found in Fig. 15.

G. Hybrid AR/VR Remote Collaboration

With the rise of hybrid work, we also experimented with enabling AR/VR remote collaboration [33], [101]. As shown in Fig. 16, a user wears an AR headset in a physical space that was previously 3D scanned and put into a VR space, in which another user joins the hybrid meeting while wearing a VR headset. To achieve this, we used Polycam for the 3D scan and Spatial.io for the Metaverse meeting platform. The in-person user wore a HoloLens 2 headset, while the remote user wore a Quest 2 headset. The in-person user only saw virtual avatars and virtual annotations (e.g., the yellow "test" note shown in Fig. 16(a)), while seeing the physical space and no 3D scan. The remote user similarly saw the virtual avatars and annotations, but saw the 3D scanned environment. Virtual-to-physical alignment was accomplished by the in-person AR user by simply adjusting the virtual environment such that the yellow "test" note appeared appropriately in the same physical and virtual location.

The experience was quite magical as users reported feeling a strong sense of presence, as though the colleague was truly with them in the AR and VR environments. Unfortunately, Spatial.io dropped support for HoloLens 2, deeming the proof-of-concept no longer usable.

V. Discussion

In this section, we describe UX experience and lessons learned overall (Section V-A), a more detailed list of identified use cases (Section V-B), public demos (Section V-C), notes on operationalization (Section V-D), and future work (Section V-E).

A. Experience and Lessons Learned

We begin this section by going through our previously defined list of important UX considerations (see Section III-A for detailed definitions of each characteristic):

1) *Ease of Use:* For most of the platforms it was fairly easy to get set up and begin using the technology. However, many quickly made interaction and communication with other users quite a bit harder. For example, users in NOWHERE would get stuck on each other, and audio falloff was too drastic and communication suffered. Meta Workrooms did a great job at capturing facial gestures on avatars that avoided uncanny valley, but avatars did not have legs which made users feel uncomfortable. Additionally, like other platforms, the avatars that users could personalize only allowed for customizing to the extent of what the tech world thought people might look like. Generally this leads to a lack of inclusivity. Almost all platforms lacked the ability to customize a space to a level of detail that would facilitate use cases at Lab.
2) *Accessibility:* Many platforms did not meet most accessibility standards; for example, if you experience vision impairment you cannot really leverage the platform. Fortunately, WebXR has made it easier for many companies to create multi-platform applications, thus increasing accessibility. Additionally, platforms that are device specific, introduce the issue of accessibility due to cost. Even though the Quest 2 is significantly cheaper that the Quest Pro or HoloLens 2, it is still an additional cost that might not scale for larger teams, thus possibly leading to inequalities in how teams might interact.
3) *User Journey:* As mentioned above, the user journey to onboard and get set up was fairly easy for most platforms. Mozilla Hubs was notably the easiest to join a meeting of the evaluated platforms.
4) *Ergonomics/Comfort:* Many users experienced discomfort wearing VR headsets for long periods of time, especially when using eyeglasses with the headset. Users were always warned to take breaks if such discomfort occurred. Prescription lens inserts were found to help immensely for any users who normally wear eyeglasses. In one instance, when testing the Meta Quest Pro, several users reported strong eye fatigue and headaches, prompting the small group meeting to end early. Overall, after some initial adjustment and becoming acquainted with the headsets, most users were able to wear the VR headset for sufficient periods of time to engage in metaverse meetings. Further investigation should be done to quantify the extent of time users are able to participate in such meetings.
5) *Audio Quality:* Most platforms supported some form of spatial audio that allowed for both small 1-on-1 or small group conversations, as well as presenter (or broadcaster style) communication where one person addresses all other meeting participants. For example, Gather.Town has "private areas" for small group conversations and "spotlight tiles" for broadcasting to everyone in the meeting. These audio features are much needed, but still need to be further developed and tested, because most of the platforms had less than ideal spatial audio fall off, or even jarring audio interactions.
6) *Ability to Express Yourself:* At a high-level, we found that for users wearing VR headsets, the styles of interaction appeared to be more similar to real-life interaction compared to traditional video conferencing (a finding others have noticed too [102]). For example, instead of barely turning one's head in a video conference meeting (due to always looking straight ahead at the 2D screen), in a VR meeting, one sees and hears users in 3D to the left and the right, as if they were in a real physical meeting space. However, there were also many issues discovered; for example, as mentioned in Section IV-A, in many instances avatars were seen moving in strange ways due to the users' VR controllers being placed down or not being tracked correctly.
7) *"Uncanny Valley":* Many of the platforms we explored left the user in a state of discomfort due to the technology not being matured enough, virtual representations failing to capture the user's presence well enough, and platforms being overly hardware specific. And similarly to Bonfert et al. [102], we also noticed that many people still prefer traditional video conferencing due to the ability to see each others' faces. Oddly Gather.Town, because of its 8 b customizable avatars, left users more comfortable interacting with users that had their videos off. In the future, more realistic avatar technologies may be available to overcome these issues [20], [103], and when partnered with well developed experience design, UX, and interaction design, they will further mimic real-life interaction and avoid uncanny valley.
8) *Support of Specific Meeting Types:* In our investigation, we focused on only a subset of the meeting types—all-hands (Section IV-A), working meetings and standup meetings (Section IV-C), and poster events (Section IV-B). The main portion of large all-hands meetings is mostly one or more people speaking and possibly presenting a slide deck; as such, the need for 3D spatial

interaction appears to be less pronounced compared to meetings where a discussion takes place. In meetings that have more of a discussion, the desire to express oneself and see and hear others spatially around you is typically greater. On the other hand, many users felt that the "uncanny valley" eeriness sometimes outweighed any benefit gained from the feeling of being immersed in a 3D environment. Thus, many resorted back to either traditional video conferencing applications, or something in between, like Gather.Town, where there was still some spatial interaction (albeit 2D) with most communication still resorting to video calls.

Overall, we learned that both 2D platforms (e.g., Gather.Town) and 3D platforms that allowed for custom 3D environments (e.g., Spatial and Hubs) worked the best overall. Perhaps somewhat surprisingly, the 2D platform Gather.Town was the most used platform overall; this was due to several key reasons.

First, 2D spatial platforms afford to users the ability to be *spatially* present in the space, which normal video calls do not. This facilitates natural interactions that are more organic and are also more comparable to being in-person. Although less than VR, a certain level of immersion is still possible because you can replicate physical spaces to a certain extent and navigate them together. In one instance, several members of the division picked seats at desks in a Gather.Town virtual office space that was made to be a replica of our team's office; those employees who had physical desks in the office virtually sat at corresponding virtual desks. In another instance, our team was able to give tours of major Lab locations to people in Gather.Town (e.g., see Section IV-D and Fig. 12), with each location being approximately spatially located relative to each other as in real life. By placing the major Lab locations in such a way, a shared spatial understanding could also promote team building by allowing for groups to understand and explore spaces together.

Second, 2D spatial platforms with the ability to allow for customization also can foster teams to celebrate recent events or communicate reactions to recent events or news. An example of this is when a team member created a digital message to the team after a town hall, which engaged the team and led to team bonding. Additionally, if the platform can leverage the Internet for content creation, one can have much more complex communications through various multimedia. This was utilized for the virtual tour of JPL, integrating with existing JPL virtual tour content available online.

Third, 2D spatial platforms do not try to create a full virtual avatar that is photorealistic, and thus it never approaches the uncanny valley. For example, in Gather.Town, users can customize an 8-bit styled character in any way that they like, and change or update it at any time. This also breaks away from the issue most other platforms have with representation of 3D avatar body types, where platforms only cater to a select few body types (e.g., one team member has wider shoulders which made the 3D scan of their head float over their VR avatar's body). Also, unlike platforms that only rely on avatar interaction, 2D platforms resort to video calls to capture micro interactions and nuanced communication (e.g., facial gestures and body language). This is something lost in many VR platforms. Finally, for people that are more introverted or Zoom-fatigued, they can still successfully engage with team members without having to rely on their video feeds. Interactions like exploding confetti and dancing are silent but easy to understand communication that does not rely on seeing the user's face.

Customizable VR platforms also worked well for several reasons. First, like 2D spatial platforms, VR platforms allow users to be spatially present in the environment, facilitating more natural interactions compared to traditional video conferencing. Having spatial audio allowed users to have small group conversations just like in real life. Second, while VR avatar technology can possibly enter the uncanny valley, it was still useful to have semi-photorealistic avatars to help recognize others in a large VR meeting environment. For some users, they appreciated this aspect of seeing others in an immersive way to feel like they were together [72], [73]. Third, the ability to import custom 3D scans of physical places was very useful to bring employees a sense of being back at the office, especially during the height of the pandemic. As noted in Section IV-A, many employees had not seen the office in-person since the pandemic had started or had never seen it, in the case of newly hired employees.

Finally, the overall main lesson learned was that while many platforms bring real value to hybrid and remote work meetings, the amount of added value is typically lower than the usability adoption cost to warrant fully switching over to any platform from traditional video conferencing systems. While some newer technologies may tout lower financial costs (e.g., licensing fees, etc.), there is still the adoption cost related to usability to consider. In some situations (e.g., CAD visualization, as mentioned in Section IV-E), the value-add can truly be game-changing and fully warrants the adoption cost. However, for many meeting types (cf. Table I), the various usability issues (e.g., inability to avoid uncanny valley) and lack of ability for nuanced communication (e.g., micro-interactions) have caused the adoption cost to outweigh the benefits of using the platforms. In addition, it should be noted that the usability adoption cost is higher in general for metaverse-related technologies because it is a shift in interaction paradigm, from traditional windows interfaces to *spatial* interfaces (either in 2D or 3D). There is also an aspect of serendipity and persistence that the metaverse brings too, which also requires a change in interaction.

B. Identified Use Cases

While our Welcome to Our Metaverse project was only able to conduct several case studies (Section IV), we were able to identify a variety of use cases during the project for which metaverse technologies may provide game-changing value. Below, we enumerate several of these use cases, grouping them into three main categories:

1) *Training:* Virtual training environments can provide immersive, interactive experiences which enable students to be more engaged when acquiring new skill sets. This can increase the amount of opportunities for users to participate in real-world scenarios and high-pressure situations, and allow users to make mistakes virtually without

endangering the safety of themselves or others. It can reduce training time and also lower the chances of mistakes being made in the future. A major challenge for this use case is develop the educational material in the proper format to truly gain the full advantage of immersive training.

One specific example is mission operations training, where it is important to quickly train new teams, especially in international settings and for remotely distributed teams. Having the ability to virtually bring individuals together, especially in a virtual environment that replicates the future physical mission operations space (see Section IV-F), has the potential to drastically reduce training time for a team. For example, needing to align individuals' schedules and ensure all the compute infrastructure is already set up can take time; virtual training has the potential to side step these issues. However, a significant challenge here is the cost of setting up a replica virtual environment for the given team with current COTS tools in a way that does not introduce distracting elements.

2) *Virtual Meetings:* Instead of participating in a traditional video call, immersive virtual meetings have given participants the opportunity to personalize their avatar and choose how they want to appear in a virtual environment. The main challenge has been that virtual meetings are only able to replace face-to-face interactions to a certain extent and the overall adoption cost generally still outweighs the benefits from virtual metaverse meetings. This is due to the need to build and design these spaces, and the fact that in most cases the technology is not mature enough.

A specific example of this use case is remote on-boarding, where the metaverse can enhance the user's sense of belonging within the organization. This allows new employees to tour the workplace within a 3D environment and gain a better understanding of the company's culture. In addition, employees who are dispersed across the globe can connect in an immersive environment and foster better relationships. The main challenge faced is the lack of nuanced face-to-face interaction that in-person onboarding provides.

Finally, as described in Section IV-D, it can be very beneficial to provide virtual tours for communities that are unable to physically come to lab due to lack of time, funding, or other restrictions. The main challenge here is providing an immersive and realistic experience for users. NERFs [84] and 3D Gaussian Splatting [104] approaches may soon offer a solution to the lack of accuracy in physically reconstructed reality for this use case. In addition, replicating presence and engagement that one would have in person is an extremely challenging problem.

3) *Data Visualization:* Metaverse technologies have enabled new ways of visualizing data. Being immersed in high-dimensional datasets has the potential to lead to novel insights, increase communication between team members, and to quickly explore data in ways traditional 2D controls do not allow. One example is engineering data visualization, where visualizing CAD models through augmented reality has made it possible for viewers to easily understand and discuss the contents of the displayed CAD model. For example, this recently became useful for engineers and scientists to visualize NISAR [105] at full-scale during the assembly process in Pasadena, California, before the satellite was transported to India; see Fig. 17.

Another example is science data visualization for scientists to explore data in three dimensions compared to traditional displays [51]. For Earth science, in particular, there is a vast amount of satellite produced data covering the entire globe; such data is not static, but time-varying and also often contains vertical columns of information for each location on Earth, furthering emphasizing the need for novel ways to explore the data beyond 2D screens. Specific examples include precipitation [106] and ocean circulation flows [107], where better understanding how these natural processes work can lead to better prediction of hurricane events, sea level rise, etc. The main challenge

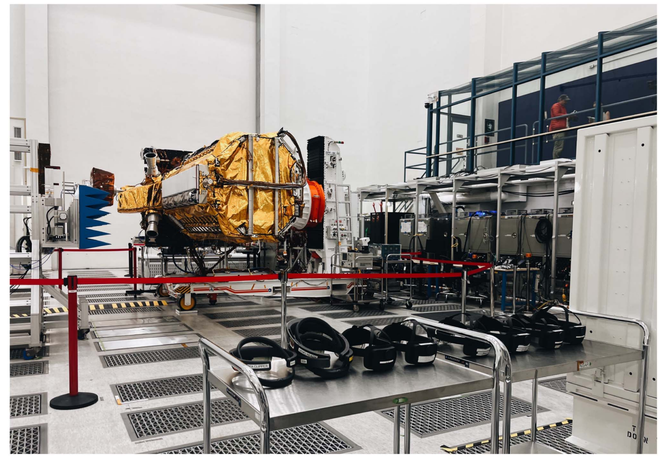


Fig. 17. HoloLens AR headsets using ProtoSpace ready for use in a cleanroom at JPL next to the NISAR spacecraft.

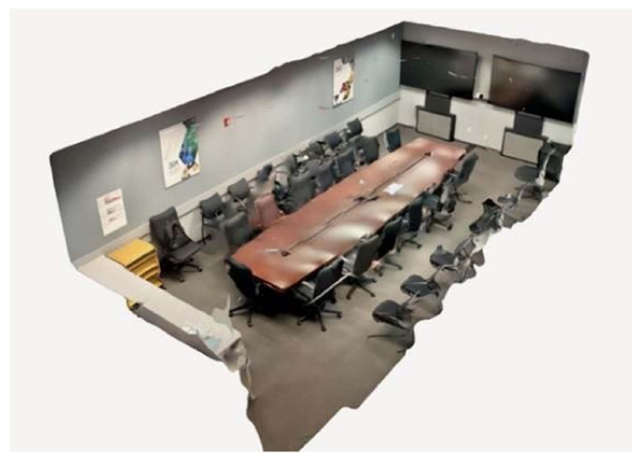
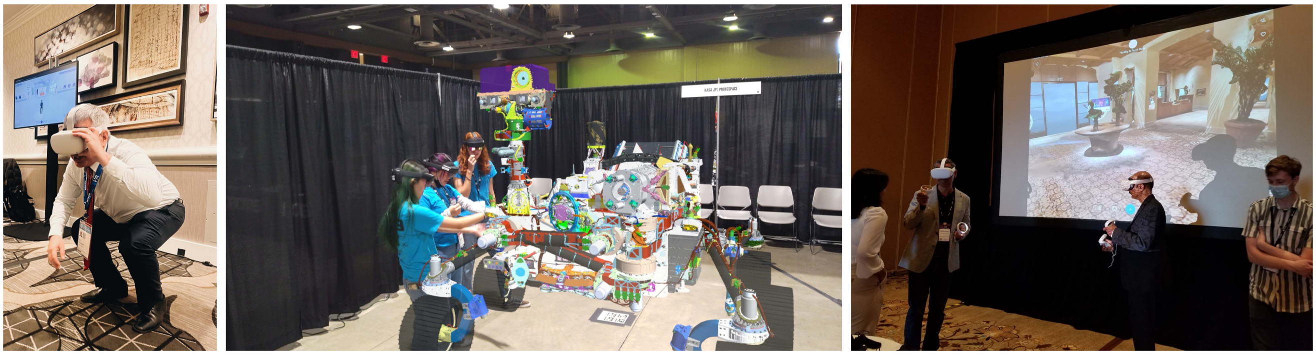


Fig. 18. Via 3D scanning, a "dollhouse" view of a conference room can be made available for conference room previews (see Section V-B for more details).



(a) 2023 U.S. Mayor's Conference.
(b) JPL's ProtoSpace AR CAD collaborative visualization tool was demonstrated at the robotics XPRIZE event [111].
(c) CIO100 Awards Demonstration.

Fig. 19. Showcasing the ability to explore 3D scanned areas in VR, and to collaboratively view mechanical CAD models of spacecraft in AR.

here is producing the proper data pipelines to ingest and render such massive datasets appropriately.

Finally, a simpler example would be novel ways to visualize conference rooms. With over 300 conference rooms in over 60 buildings, it can be challenging for a JPL employee to know what a specific conference room looks like. 3D scanning apps can be used to get a "dollhouse" style view of a conference room (see Fig. 18). This gives a preview of what a conference room looks like without having to physically check it, and this provides familiarity to those attending the meeting that will take place in the conference room. The main challenge is the creation of a digital a pipeline from 3D scan to an existing conference room digital infrastructure.

C. Showcases/Public Demos

While the focus of our efforts were on investigating internal use cases and iterating with employee end users, the project also had the opportunity to gain feedback from the community and to inspire others on the possibilities of metaverse technologies. Over the course of the project, we demonstrated various aspects of the technology at a variety of venues, including but not limited to: the CIO100 Awards 2022 event [108], the 2022 NISAR Science Community Workshop [105], [109], the 2022 XPRIZE AVATAR event [110], and the 2023 Mayor's Conference [111]. Appropriate hygiene (e.g., Cleanbox [112] and hand sanitizer) were utilized as much as possible during all events. Fig. 19 shows a few examples of demoing to the public at a subset of these events. Overall, the reception of the technology was very strong and provided a strong educational tool for helping others understand not only the technology but broader science and engineering aspects as well.

D. Operationalization Notes

To guarantee integration of hardware and software at JPL, every item must be registered with the cybersecurity team, undergo necessary testing, and meet the specified minimum requirements. After fulfilling the minimum requirements, the final operationalization of a platform must undergo a rigorous process with the Project Management Office (PMO). The case studies (Section IV) presented here are currently in the process of moving from sandboxed prototypes, with very limited reach, to being made fully operational to JPL employees at large.

E. Future Work/Outlook

The overall outlook for the metaverse is strong. Immediate next steps for this project are to solidify all identified use cases (Section V-B) and to pursue the ones with the highest value-add and lowest adoption cost. The merging of augmented reality and virtual reality through 3D scanned physical environments, as referenced in Section IV-G, has potential to strongly increase the feeling of presence and accessibility for hybrid teams and the benefits should be further investigated in future work.

More broadly, metaverse technologies are rapidly developing and maturing. While it is impossible to capture all trends, some areas our team has identified to keep a close eye on are:

- Glasses-free stereo displays—in recent years, there has been a huge increase in availability of auto-stereoscopic displays (e.g., Looking Glass [113], Lume Pad [114], etc.), including entire teleconferencing systems custom-built with such displays (e.g., Project Starline [115]).
- Generative AI and Large language models (LLMs) have exploded in popularity in recent years. LLMs and artificial intelligence (AI) models have the potential to create more immersive metaverse experiences for both consumers and enterprises. For example, LLMs can be used to allow users to more interactively ask questions about a space through conversational chatbot virtual agents. In addition, AI can reduce the time to author immersive experiences through helping developers write code [116] or author content [117].
- As mentioned in Section III-E, NERFs [84] have recently gained immense popularity and have strong potential to enable the most immersive experience of 3D captured reality yet. Even more recently, 3D Gaussian Splatting [104] has also emerged as a possible way forward to more accurate and real-time novel view synthesis. It may be these technologies will soon be enough to push past any issues of "uncanny valley" and poorly 3D reconstructed spaces.

- Photorealistic Avatars—while most current software may still bring about an "uncanny valley" feeling for most users, there has been a strong push toward highly photorealistic avatars usable by immersive platforms [20], [103]. It appears that it is not a question of "if" but "when" this will fully be available to the industry at large and compatible with typical headsets.
- Portable metaverse experiences—while we typically think of pushing all the hardware technology needed for the metaverse into a single headset, an interesting approach is to utilize recent software and hardware advances to create new portable metaverse experiences. "Metaverse in my carry-on bag" is one such example, showing that it is now very easy to package up new immersive experiences for portable travel [118].

VI. Conclusion

In conclusion, we presented an overview of our investigation into applying metaverse technologies to our organization at large. We started by considering the user experience needs and conducting an initial investigation into a variety of metaverse applications. We then concentrated on several focused case studies, developing initial prototypes for more detailed evaluation. Finally, we presented a discussion on lessons learned, identified use cases, and a general outlook for the metaverse. Overall, on the one hand, metaverse technologies have advanced to the point to be able to bring significant value-add to the organization. On the other hand, significant barriers still exist, causing the adoption cost of the technology to remain high in many cases. Similar findings have recently been reported by the community at large [119]. We expect that as software and hardware mature in the coming months, technology adoption will continue to increase, bring us closer to fully realizing the metaverse at scale.

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