Collaboration in Virtual Reality: Survey

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***Abstract*—Virtual reality (VR) collaboration has gained particular attention in recent years, especially in industry, due to its ability to provide immersive, interactive environments that enable collaboration between users. VR enables users to feel present in a shared space and to communicate with each other. Adding natural gestures and movements to the virtual environment enables collaborators to work together more effectively. This technology has been used in many fields (gaming, healthcare, business...). However, collaboration in virtual reality also presents unique challenges, such as the problems associated with transporting information and the current status of other users. Research is in progress to address these challenges and improve the usability and efficiency of collaborative VR. Overall, collaboration in VR has the potential to revolutionize the way teams work together and presents exciting opportunities for innovation and growth in a variety of industries.**

I. Introduction

Virtual reality is a computer simulation system based on computer graphics and human-computer interaction technology [1]. There are 5 key elements to any virtual reality experience [2]: The participants are probably the most important because everything happens in their heads. A creator who designs experiences. A virtual world that describes objects and the relationships between them. Then immersion, which can refer to both mental and physical immersion. Mental immersion is the state of being committed to an experience, while physical immersion involves physically entering a medium via synthetic stimuli. And interactivity, since VR needs to respond to user actions in the environment.

3D simulations have been widely used for a long time, but their lack of immersion and interaction has made them less interesting over time. With the development of immersive technologies and tools that provide higher levels of interaction, the focus has shifted to immersive collaborative virtual environments. A collaborative virtual environment (CVE) is a type of distributed virtual reality specifically designed to allow multiple users to create, share, and manipulate information in a shared space [3], [4]. Collaboration can be symmetrical or asymmetrical depending on the similarity between users' accessibilities. Additionally, collaborative virtual environments (CVEs) allow distributed team members to collaborate synchronously or asynchronously. So far, much of CVE's work has been devoted to real-time collaboration [5], which should take into account the user's social and cognitive task characteristics. Transforming a virtual environment (VE) into a CVE requires providing task-specific information representation and communication tools, as well as an appropriate landscape for collaboration. Therefore, CVEs should be designed to support specific user collaborations and provide the tools necessary to ensure their effectiveness.

Another key aspect of CVE is the use of avatars that act as a representation of the user within the virtual world. Avatars should represent the users accurately as as possible including gestures and facial expressions to ensure effective communication and interaction between users. Also, the importance of avatars lies in their ability to help users identify each other and facilitate interaction within the virtual world.

II. Collaboration

Collaboration occurs when interactions between different individuals become deeper and more complex to communicate and achieve common long-term, interdependent, and complex goals [6]. The collaboration could be synchronous/Asynchronous if the collaborators participate at the same time or not. It could also be Symmetric/Asymmetric means that all the individuals contribute in a similar way to the tasks or differently.

A. Synchronous Vs. Asynchronous collaboration

In a collaborative virtual environment, multiple users can attend collaborative works at the same time we talk about synchronous collaboration . [7] In synchronous collaboration, co-workers can move and interact in a shared environment in real-time and at high frame rates, enabling instant communication. Collaboration should avoid conflicts between tasks and actions and requires interactive coordination between employees. [3], [8], [9]

However, distributed teams rely often on asynchronous collaboration tools due to the costs and difficulties linked to scheduling synchronous communications and geographic dispersion [5].

The Asynchronous Collaborative Virtual Environment becomes more and more important, the purpose of the system is to deal with the time and geographic conflict between users. One of the solutions is to provide version control concepts for collaborative works. That is, the system records intermediate simulation results as movie files, 3D replay files, and data files. These files are stored in the collaboration server and other co-workers can download these files, review the previous works, and resume the works, if necessary. The coworkers can analyze the intermediate results, give feedback as comments, and decide whether they reject or accept the previous works. It is similar to the version control concept in software engineering [7]. A system that enables to recording of avatars and replaying their verbal and nonverbal behavior was introduced in [5] under the name of VR-replay. 40 participants (19 female) with a mean age of 19.4 years participated in a study that aimed to investigate the effects of different conditions on participants' reports of performance satisfaction, quality of communication, perception of others, and user preference when using three asynchronous communication tools for 3D collaborative design (VR-replay, VR-audio, Desktop-Audio). Results showed that using VR-Replay improved participants' perceptions of teamwork and communication clarity, compared to VR-Audio and Desktop-Audio. Participants also preferred VR-Replay for asynchronous communication in 3D collaborative design. The study suggests that seeing each other's nonverbal cues during asynchronous communication can improve positive perceptions of partners and facilitate understanding of the work. To record and replay the VR sessions a standard named MPEG-4 was introduced in [10].

In some cases, it could need a hybrid system that uses synchronous and asynchronous collaboration features. One example in these cases is the system provided in [7].In synchronous collaboration, the system is based on a floor control mechanism (Allows only the user who has the right to make changes in the environment).In asynchronous collaboration, the system records the data and behavior to replay it. The [11] presented a methodology for developing applications that synchronize content while allowing asynchronous work with the data. Communication data is stored on the fly and broadcast to connected clients, and a data model structured as documents and items can be used. Archived information can be used for the reconstruction and analysis of work processes, and the approach can be adapted for different domains.

B. Symmetrical Vs. Asymmetrical collaboration

Symmetric collaboration is where participants can perform similar actions and have identical authority over the environment. It provides equal control and accessibility for each user, increasing flexibility and self-control from the user's perspective. Therefore, multiple tasks can be performed in parallel at the same time. The disadvantage is that the symmetric mode requires more interface resources. Privileged mode, on the other hand, is superior to symmetric mode for applications with natural routing or monitoring requirements. For security reasons, executives can monitor the pace of processes and control access to sensitive resources and regions [12], [13].

An asymmetric collaboration represents the capacity of individuals in a group to have different actions. In the case of VR, an asymmetric collaboration means the users visualize and interact with the virtual content differently [4] and access the shared environment with different devices. It can be used to guide and supervise the immersive peer [14].

Symmetric considers all the collaboration as same peers, which could boost the co-presence, immersion, and communication [14]but if participants had to move in different ways, we should then use asymmetric collaboration. In addition to that, asymmetric systems require fewer safety precautions than symmetric systems, where the user can theoretically hit each other.

A study was conducted where 36 participants to compare the asymmetry collaboration in virtual reality with two cases of symmetric collaboration, the first with both collaborators using HMD and the second where both of them are using AR-supported devices to collaborate [4]. Users were asked to manipulate some 3D objects. The results of the same study show that VR-VR is the fastest technique for these cases followed by the VR-AR technique and the AR-AR comes in the third position. The contribution behavior and coordination behavior were evaluated to deduct that all three different technique pairs seem to have the same level of cooperation level of work even when there is an asymmetric collaboration between them. During the social presence analysis, the users in asymmetric collaboration seem to have a lower sense that the pairs help each other.

In the field of education, a system named Kvasir-VR [15] was developed to add interactivity objects in the field during real field trips to a power plant. The asymmetric system allows the student to be immersed in a virtual environment where they can visit different stations manipulate educational items and navigate by using a teleportation ray. The study involved both a live networked and a non-networked standalone version of a teacher-guided virtual field trip. In the networked version, a live teacher guides small groups of students using a teacher interface and two-way communication. The standalone version uses a prerecorded teacher and a multiple-choice quiz to allow constrained responses. The teacher guides the student from a projection or TV interface. To deal with the narrow Field of View (FoV) the teacher can see themselves as mirrored in the view. 88 high school students participated in the experience, to compare the teacher-guide VR approaches. Results showed that the live networked VR field trip was more effective in terms of student learning and subjective experience. However, standalone approaches still have practical advantages such as simpler deployment and scalability for larger audiences. Another study was led in the [12], to develop a prototype for an asymmetric CVE for a virtual city tour, where the guide takes the primary role and visitors take the secondary role using virtual reality. In the preliminary study The AR part of the system was implemented on a smartphone and a wooden shovel was used as a tangible to select and display the section of the virtual city on the desk.

In the same context, in the article [16], a new concept was introduced known as Tangible Replicas, which are physical objects used in a collaborative mixed reality (MR) system to provide a more natural interaction between remote users. To set the world coordinate system in real space, the workspace is set on the base object in each site for collaboration The article describes a remote MR model in which a base physical object is chosen. The article defines the two spaces as ”equivalent” when the physical structure of the workspaces is the same, and notes that asymmetry can occur between the two spaces when a tangible object is moved in one site, causing the virtual object in the other site to change position. The article proposes replacing the virtual object with a real object on the other site to create a set of tangible replicas but notes that the problem of not being able to change the position of the real object in the remote site remains. The system was evaluated by creating a prototype system where a duplicated cube is available for each user each user has to collar the pixels of the cube. Results of the experiment showed that the pointing task could be accomplished correctly without a problem and the pointing performance in the portable replica condition was more efficient than in the fixed replica condition.

C. Examples of Collaboration

Collaboration has been used in different fields starting from business, education, engineering, industrial design, and conception...The academic and industry collaborate to fill the gap between the student’s skills and the needs of industry by developing modules and choosing the contents that will be provided to students who will face industrial challenges in the future [17]. The importance of this kind of collaboration is that makes students more engaged and motivated to study because they understand that what they are currently acquiring suits the needs of the industry. In the context of education, collaboration between different fields of students can also be valuable. Let’s take an example provided in [18] which reflects the importance of collaboration between biomedical engineering and industrial design students in developing medical devices. Industrial designers are responsible for the usability, safety, and aesthetics of the product, while engineers focus on technical aspects such as functionality and performance. Including industrial design students in projects, teams can improve the overall quality of the project by producing professional-quality, aesthetically pleasing, and functional prototypes. The collaboration also allows students to learn about each other’s discipline and the role they play on the project team. The students learn to communicate with people from different disciplines, appreciate the complementary skills of team members, and develop an appreciation for different problem-solving approaches. A cross-domain collaborative 3D design method was introduced in [19] to improve the quality and efficiency of large-scale ship development through concurrent collaboration of design and construction. The system includes interconnecting the information system between the shipyards and design institute, designing and developing a shipbuilding process and information document management system based on WEB, and integrating the business process of the project management system to manage design process documents in a unified way. Another example in the technology industry was Intel [20], a global semiconductor chip manufacturing company, that uses social computing technologies for both internal collaboration and external brand marketing. They invest in social capabilities and partner with HR to address cultural and motivational barriers for better collaboration and productivity. Intel conducts user experience research and crowd-sourcing exercises to gather feedback and identify opportunities for transformation. They face challenges due to historically siloed work practices and a reluctance to share information, limiting their ability to extract the best performance and ideas from their employees. The company's key opportunities for transformation lie in Product Design and Sales, where effective collaboration can drive innovative results faster and improve competitive advantage. The solution approach involves understanding each employee group's workflow needs and developing the solution architecture that meets those needs using a Scaled Agile Framework, HR partnership, UX design methodologies, and architecture and solution pathfinding. In the [21] This article discusses the importance of collaboration in large-scale evolving systems and proposes a framework for facilitating collaboration through the development of a collaborative architecture and supporting technology. The article suggests using an ensemble of communities working towards a common vision as the basis for collaborative architecture and proposes roles and technologies needed to support inter-community collaboration. The paper suggests integrating collaborative technologies with intelligent agent systems to improve large-scale collaboration and concludes that the proposed architecture provides a framework for developing agents that will improve collaboration. In the [22] discusses the challenges and high failure rate of supply chain collaboration (SCC) initiatives, and proposes a framework for implementing and improving SCC practices. A case study of a Vietnamese textile and apparel manufacturer, ABC, is used to examine SCC practices and identify reasons for failure. The study finds that ABC lacks effective internal collaboration, leading to ineffectiveness in operations and failures in collaboration with customers. The article concludes that SCC is crucial for successful business operations and competitive advantage, but more research is needed to understand how to implement it successfully.

III. Collaboration in Virtual Reality

Immersive collaborative virtual surroundings(CVEs) are simulations in which geographically separated individualities interact in a shared, three-dimensional, digital space using immersive virtual terrain technology. [23], [24]

A. *From Virtual Environment (VE) to Collaborative environment (CVE) [25]*

In addition to the aesthetic and design aspect, the virtual environment should allow the user to communicate and exchange information and the state of activities with other collaborators. In this section, we will consider the characteristics of a CVE.

- *Transition between shared and individual activities*: In the context of task goals the collaborators should understand and know what is being done and what the goals they want to achieve.
- *Characterizing collaborative work: Flexible and multiple viewpoints*: The environment should provide tools to define collaborative work and the way it should be represented. Also, for each type of user, the information provided should be accurate and optimal (for example the electrician will only need the wiring plans in detail not necessarily the plans for the plumbing), and also if there is confidential data it should only be visible to the concerned users.
- *Characterizing collaborative work: Sharing context*:the environment should be synchronized to all users .The user should share the current and past state and any other activities.

- *Characterizing collaborative work: Awareness of others*:the collaborators should be aware of each other .The environment should consider co-presence awareness and provide moment-to-moment awareness.
- *Characterizing collaborative work: Negotiation and communication*:60% to 90% of our communication is body language and gestures.The solution may be to keep these to represent the users as avatars in VE.

B. Example of application of collaboration in Virtual Reality

Collaborative Virtual Environments have been used in different sectors. In the [26] The CVE technology has been implemented in construction planning and building maintenance. A maintenance system for exterior walls was created, incorporating interactive techniques and input devices for visual exploration tasks. The system provides information on different types of coating materials, application processes, anomalies, and repair works. The virtual model created allows users to visually and interactively analyze anomalies observed in an inspection of the real building and predict corresponding repair work. Another example is in [27] the VR is used in design and manufacturing processes in the aerospace industry.

C. Advantages and Limitations

Collaboration in virtual reality (VR) has been a growing area of research in recent years. VR allows individuals to work together in a shared immersive environment, regardless of their physical location. This has the potential to revolutionize the way teams collaborate, as it enables them to work together in ways that were previously impossible [28]. The design space of collaboration in VR highlights the potential benefits of this technology, including enhanced communication, increased engagement, and improved decision-making [29]. Virtual reality collaboration provides a lot of opportunities to increase engagement, by creating a more engaging experience than traditional collaboration tools, which can help increase productivity and motivation. Also, it improves communication because it allows a more natural communication experience, allowing team members to better understand each other's intentions and emotions [29]. And for better decision making VR can enable more effective collaboration by providing a shared space where team members can work together to make decisions [30]. A study to analyze the effect of online Education using CVR showed that students tend to learn and retain more in interactive environments rather than in a monotonous learning process. The author said that the challenge was to make the applications compatible with all users [31]. However, there are also some disadvantages to VR collaboration, including the cost of VR hardware and software which can be expensive, and may limit its adoption for some teams. Also, regarding the technical challenges, VR can be complex to set up and use, which may require additional training for team members. And, with the limited physical interaction, VR may not fully replicate the physical interaction of in-person collaboration, which could be a drawback for some teams [32] [33].

IV. Related Work

A. Interaction in collaborative VR

In a collaborative virtual reality environment the user should interact with the objects in the environment, with other users, and with the environment itself. Different techniques were proposed to approach these problems.

Hand gestures are a posture or movement of the user's upper limbs. Through these gestures, the user can send different commands and information [34]. The gestures can be classified based on the spatiotemporal as statistics mean only the spatial posture and dynamic that consider the movement. Or based on the gesture semantics, the unintentional; movement of the hand/arm doesn't provide any information, and intentional movement where there is meaningful information. Or based on the interaction mode, media gesture, direct gesture, and indirect gesture [34]. Another multimodal technique was considered to interact with the object in VR, the Gaze + Pinch technique, where the user selects the object by fixing his eyes on the target object and he can manipulate it with hands. [4]. The Gaze + Pinch technique was evaluated, by integrating it into a UI system and multiple applications. The combination is intuitive to use and offers a feeling of magical interaction, but requires careful design due to limitations in the hand and accurate eye monitoring. Basic interactions are easy to use and comfortable, but more complex menu interactions are challenging [4].

There are two possibilities for the interaction in VR either the user uses the controllers as a pointer or without controllers using the virtual hand technique (3D interface metaphor that mimics the grasping and posing of the real object) [4]. The use of the virtual hand is more intuitive but it limits the user to reachable area [35].On the other hand, the Virtual pointer overcomes the limitation of the space the user can manipulate far objects. However, there might be some confusion between selecting the object and manipulating it [36].

In the context of comparing the distant and virtual hand manipulation A study was landed in the [4] they compared the time required to finish each docking in the two cases to compare between the two techniques. The result of the experience shows that the Virtual Hand allows faster forming than the distant Technique. However, there is no significant statistical in the level of workload (using the NASA TLX questionnaire).

A study was led in [36] to compare two different techniques of interaction: pointing-base interaction (use the hand and the arm to manipulate the reachable object or select the distant object) and the eye movement where the user uses the eye tracking to manipulate and select the object is located in a different position in the virtual world. In the latter technique when the user fixes his sight on one object the system highlights these objects and exposes it. 24 participants with an average age of 22 years participated in the experience. The results show that eye movement allows faster and higher performance in a distant environment compared to pointing. However, in a close environment, there is no significant difference between the two. Also, the spatial memory of the user is worse in eye movement. Most participants admitted to the eye movement technique because they found it easier and more natural to use. Object manipulation, finding the object should be synchronized across every user which may cause conflict when two users manipulate the same object. The problem is solved with the ownership (only one user has the right to manipulate the object)for the movement the author presents teleportation to reach some object and resolve the problem of the limitations of the physical world. [37]

Another important task in the collaborative virtual environment is manipulating the virtual object by more than one user simultaneously. Different studies were developed in this context. In the [38], the SkeweR system was introduced. It allows two users to move the same virtual object in 3D at the same time, it combines the separate user's manipulation to apply a final transformation to the object. What makes this system different from the previous one is that it allows more natural manipulation of the object by choosing the point of control while the others allow the orientation and translation according to the center of the object. The controller of the user is attached to a choice point in the object, the motion of the user controller determines the partial new orientation and position of the object. Then, the final orientation and position are calculated from the two partial ones of the two users. The system can be extended to three users. Another different system was introduced in [39] that combines the interaction techniques instead of combining the motions of the users. The system is based on the Collaboration Metaphor; a concept that allows the combination of different techniques of interaction. It is all about separating the degree of freedom of the object that each user can manipulate, considering two interaction techniques: Simple Virtual Hand and Ray-casting. And to increase awareness the authors suggest displaying some information on the object (changing the color based on the state of the object). A primary experience with 12 users divided into pairs, was led to see if the cooperative manipulation increases the efficiency compared to a single-user manipulation and to evaluate the time the users spend to switch from single to cooperative manipulation. The results show that the cooperative increases performance. However, the single manipulation is still simple to use. The learning time depends on the individual, which means if the user has quickly learned the single manipulation, he/she can quickly learn the cooperative.

Communication

Communication is the exchange of data, knowledge, and skills between different people who have a common symbol or media. [40] Virtual Reality allows people to have immersive communication in a shared virtual environment. The challenge of using these technologies in communication is considering facial expressions, body gestures, and eye gaze in real time.

Effective communication in virtual reality applications requires introducing body language and facial expression [41]. Facial expressions particularly provide a site about the state of a person, their reaction, and feedback about what is being said [23]. It helps understand others by providing indicators of their personality and emotions. A new VR communication system that mimics users' movement, facial expressions, and speech to render the data collected into different types of avatar representation in real-time was introduced in [41]. The system allows for two users to communicate through a virtual avatar in a 3D environment, with one user animating the avatar's body and facial expressions using audio, and the other user viewing the avatar through an HMD. The system uses HTC Vive trackers and inverse kinematics to control the avatar's body movements, and the iPhone X depth camera and Live Link plug-in to animate the avatar's facial expressions in real time. Audio input data is also supported. The system can be used for any VR application that requires virtual avatar communication. The limitation of this system is that it requires one user to be embodied with a virtual avatar and the other to view and communicate with it. A study in [42]investigated how facial expressions affect social presence in virtual reality (VR) systems that aim to bridge the physical separation between people. 48 participants aged between 17 and 47 with varying levels of VR experience have assisted with the experience. the results show that facial expressions positively influence social presence in VR environments. Eye movements resulted in the highest levels of co-presence during verbal explanations and aided in determining the direction of the other person's attention and made social interaction feel more natural and realistic, while mouth movements evoked co-presence more prominently than neutral facial expressions and were found to help understand what the other person is saying and detecting their emotions. However, some participants found the facial animations distracting or irritating. In the context of facial expression recognition and mapping different approaches were developed. In the [43] a technology that maps facial expressions between virtual avatars and users wearing Head-Mounted Displays (HMDs) was introduced uses retro-reflective photoelectric sensors inside the HMD to measure distance and estimate the user's facial expressions. The system achieved 88% accuracy and can reproduce facial expressions in real-time, enabling estimation and reconstruction of facial expressions corresponding to the user's emotional changes. It uses photo-reflective sensors to measure distances between the sensors and the skin surface for each facial expression, and two neural networks are trained for multi-class classification and regression to map between a user and a virtual avatar. A similar system was provided in [44] using electromyography (EMG) sensors attached to the headset frame to track facial muscle movements and generate personalized blend shapes associated with seven facial action units (AUs) on the most emotionally salient facial parts.

Another important way to communicate between users is using *Gestures*, the posture or the movement of the upper limbs of the user [34]. People usually attract the attention of others by moving their hands, The two components of gestures are movement and meaning. The gestures can be either static or dynamic. They can also be manipulative gestures that change the state of objects or communicative that have a specific information function.

A study was led in [3] to compare three different conditions VR with Symbolic gestures, without symbolic gestures, and face-to-face in the context of brainstorming .18 participants (16 males, 2 females) participated in the experiment. The study collected various data related to behavior and psychology. The data included the number of ideas generated, total utterance duration, utterance frequency, the balance of participation, usage count of symbolic gestures, and questionnaires. The results show that using symbolic gestures in virtual reality (VR) can improve the user interface for brainstorming, leading to a higher average number of ideas created compared to face-to-face interactions. There was no significant difference in total utterance duration or frequency. Nodding and thinking gestures were most frequently used, and positive gestures like Good, Yes, and Laugh were commonly used. Questionnaires showed that using symbolic gestures to express feelings and intents improved perceived behavioral interdependence in VR space. The study also found that remote communication via standard avatars in VR space decreases social presence, but using symbolic gestures can improve social presence.

Magic is a new system introduced in [45], which aims to improve remote collaboration in virtual environments by enhancing pointing agreement (the measurement of what the users see in common when the pointing gesture is used). It enables the use of natural gestures and reduces the separation between task space and personal space. To deal with the problem of occlusion Magic ensures that both users have the same points of view of the workspace. To evaluate Magic a study case was led to see if a face-to-face collaboration setting coupled with manipulation that enables perspective sharing can improve the understanding of the proximal pointing gestures and increase workspace awareness without distracting users from the main task. The participants need to complete a collaborative pointing task under two different conditions: MAGIC Face-to-Face and Veridical Face-to-Face. The study found that MAGIC, a novel method for shared 3D space pointing, improves pointing agreement and co-presence in face-to-face collaboration without negatively affecting task completion time. Pointing agreement was measured by the Jaccard Similarity Coefficient, which characterizes all possible scenarios in the experiments. The study also collected data on user preferences and found that users reported feeling more co-present with their remote partner when using MAGIC. While there was no statistically significant difference in perceived message understanding between conditions, users commented that targets were easier to understand under MAGIC.

B. Navigation in Virtual Reality

Navigation is the most prevalent form of user interaction in a virtual environment [46]. A CVE allows the users to explore a shared environment [47], [48]. However, to stay together each user has to have a track of the other members [48].

First, let's explore some techniques for navigation in a virtual environment. One common technique to navigate in the virtual world is to travel by physical walking within a restricted tracking area [49], [50]. Since it's the locomotion interface that we use every day [51], it provides the most natural, intuitive, and direct way to move in the virtual environment. However, the problem with this technique is that most of the time the real world is smaller than the virtual world so if the user uses natural walking he will reach the limits of the real world quickly [51]. The need for a non-natural technique to navigate in the virtual world introduces a motion sickness [51], [52]. Overcoming the limitation of physical walking is linked to the limits of the real world. One technique called *The Magic Barrier Tape* [51] was conceded to avoid the mismatch between the restricted sizes workplace and the potentially infinite size of the virtual scene. In this technique, the user moves in the infinite workspace, but virtual boundaries with a "Do not cross" warning give the user a reference to the limited reel space. The Magic Barrier Tape was evaluated by comparing it to two other existing navigation techniques, the results show that the current studied technique made the shorter completion time (The time required to finish the trial)compared to the two others. Also, the users found this technique more natural and less tiring. However, it's less precise since it's meant for coarse positioning between fine positioning tasks instead of precise path following [51]. The technique can be improved by Redirection With Distortion (IRD) [53], using distractors to stop the user when rotating the predicted user path back toward the center of the tracker space. The IRD was evaluated by comparing it to real walking (RW) measuring the user's navigational ability. The result shows that IRD is no worse than the RW, but the problem with IRD is that the user travels farther compared to the RW [53].

Travel by teleportation, on the other hand, reduces the mismatching and motion sickness. [54], [55]. Three types of teleportation were compared in a study [54] Teleportation, Animated interpolation, and pulsed interpolation. The teleportation of the user position and rotation change instantly, the process of these changes cannot be seen [54], [55]. In the Animated interpolation, with a smooth viewpoint motion from one state to another the user can observe the process of being moving [54]. The last one is pulsed interpolation where the change of the state occurs by dividing the trajectory into intermediate points. The results show that the participants track easier space using teleportation. While the animated interpolation allows the highest level of spatial awareness and was rated worst in terms of sickness. The lack of the relation between the origin and target position can lead to low spatial awareness [55]. The other type of travel in virtual reality by teleportation is the *Jumping* technique, which limits the range of possible teleportation targets to visible space. Consequently, the distant space can only be reached by the consecutive jumping [55]. A study was laid to compare the reel walking with the jumping, the results show that the jumping helps some participants to achieve similar spatial updating performances to the RW.

In the case of group navigation, one technique was introduced in [56] which is World in Miniature (WiM). This is a representation of the entire environment in a small model. The technique is asymmetric because there is always a guide who decides the position and the time for the navigation. To evaluate the technique a case study was led to compare WiM with another technique. The study measured user performance, discomfort, and qualitative feedback. The results showed that the task completion time significantly increased with higher difficulty levels, but there were no statistically significant effects on the technique's main effect and placement error. Both techniques induced some discomfort symptoms, with the guide experiencing more nausea in the WiM technique. The study identified the potential benefits and limitations of both techniques and suggested that a combination of both could be effective. The study also highlighted areas for future research, such as scalability and the use of AI to enhance user experiences and optimize group-forming patterns. [56] Another, technique was proposed in [57] named the Multi-Ray Jumping technique, which uses the jumping studied earlier for group navigation in VE. In the same study an experience was led with three types of navigation to study the limitation of the naive jumping group technique with an asymmetric rule (there is the navigator and all other persons in the group will be teleported passively by the navigator), the result shows that a lot of participants needed a space reorientation, also they are often confused with the target position since they can only see the one where the navigator point, and they were often placed on the wall because the navigator ignores the relative position of each one. The solution for these problems was introduced in the Multi-Ray Jumping technique, the idea behind this technique is to show from each controller of each person within a group a ray that starts from its controller and point to the target position, all the users of the group have the control of the jumping means they can press the button in the controllers to start the jumping [57]. Two different experiences led to the evaluation of the technique. The first one shows that the amount of simulator sickness perceived during Multi-Ray Jumping in the passenger role is close to the one during active single-user jumping. The second reveals that the Multi-Ray outperforms the Single-Ray technique in terms of shorter times and lower cognitive load with large effect size and low placement error. However, the time spent on target specification was not significantly different in both cases. [57]

C. *User representation in Virtual Reality*

Displaying avatars or remote visualization is very useful for the awareness of the collaborative space and other collaborators. [27] Several studies aim to explore the impact of user appearance in a virtual Reality environment [58].

The study examined the impact of different avatar representations on performance and experience during simple walking tasks in virtual reality. The results showed no significant differences in gait variability and subjective performance ratings across different avatar appearances, but participants did perceive differences in the degree of realism and possibility to act. The study suggests that for simple walking tasks in VR, egocentric self-representation may not have a significant impact on performance, but further research is needed to explore this in more complex motor tasks and with patients who have physical impairments [58]. Other studies focused on measuring the sense of ownership. The level of avatar realism can be decomposed into visual and motion fidelity. Visual fidelity can be achieved through photo-realistic virtual characters or by creating self-alike avatars. Motion fidelity can be achieved through real-time motion tracking systems [59]. The same paper presents a technical pipeline for generating body ownership illusion with self-alike avatars in VR. To evaluate the model, seven participants each had two different self-avatars: one with high visual fidelity and one with low visual fidelity. Participants were asked to practice their presentation in front of a virtual mirror in VR while wearing a VR headset to measure the level of uncanny valley and embodiment. The results show that avatar appearance realism had an impact on both uncanny valley and embodiment and that participants reacted more positively towards the cartoon-like avatar than the realistic one, in terms of attractiveness, humanness, eeriness, and spine-tingling, they also found the cartoon-like avatar significantly more attractive than the realistic one. They had lower body ownership and external appearance illusion with the cartoon-like avatar, but a higher sense of agency and control and location of the body with the cartoon-like one. In the same paper, the Second study aimed to investigate the effects of avatar motion-fidelity on the Uncanny Valley and Embodiment phenomena, and also included an analysis of participants' gaze and movement. Two generic gender-matched avatars (realistic and cartoon-like) were used for each participant. In the [60] three different types of avatar design for AR remote instruction systems were compared in terms of usability. The three designs are a full-body avatar, a hand-and-arm avatar, and a hand-only avatar. The study found that the full-body avatar condition had higher usability than the hand-only condition, and participants found it easier to track the full-body avatar. Another study led to compare three different types of avatars in [61] a user study: idle avatars with complete bodies and pre-defined animations, mapped avatars with complete bodies and one-to-one mapping of user movements, and social VR avatars with only head and hand representations and one-to-one mapping. The study aims to understand how the visual representation of avatars and their body movements affect communication quality. The study considers social presence, defined as the perceived presence of another intelligent being, as a measure of communication quality. It found a significant effect of avatar appearance on presence, with the Mapped condition resulting in the highest presence. There was no significant difference in cognitive load based on avatar appearance. The result also shows some effects for sub-factors of social presence, with higher co-presence and behavioral interdependence in the Mapped and SocialVR conditions compared to the Idle condition. However, there was no significant difference in the overall factor of social presence, and the sub-factors related to emotional and affective states had lower results possibly due to the system's inability to represent facial expressions and finger posture in detail. The study found that an avatar with a complete body that mapped the user's movements generated the highest copresence and behavioral interdependence. However, an avatar with only a head and hands was not significantly worse and even better than using a complete avatar body with pre-defined animations. In the [62] the authors propose a method for enabling hand-contact interaction between remote users in a social telepresence environment, using avatar-mediated communication. The approach involves developing classifiers to recognize the users' intention for contact interaction and adjusting the avatar's pose to maintain contact with the other user when the two users attempt to make contact. During the contact phase, inverse kinematics is used to determine the avatar's arm's pose to initiate and maintain natural contact with the other user's hand. The system was for handshake but could be extended to other types of contact. The accuracy of the classifiers needs to be improved to distinguish handshakes from other similar-looking motions. The method expands the possibilities of avatar-mediated social telepresence by allowing for hand-contact interaction between remote users.

D. Framework for collaboration in VR

CollaboVR [63], a framework for multi-user communication in virtual reality that allows users to share freehand drawings, convert 2D sketches into 3D models, and generate procedural animations in real time. It supports sketching, audio communication, and collaboration in 3D. The system has three custom layouts - integrated, mirrored, and projective - to reduce visual clutter, increase eye contact, or adapt to different use cases. The system leverages a cloud architecture to minimize the computational expense for VR clients. It provides various configurations for user arrangements and input modes. The three user arrangements provided are side-by-side(integrated), face-to-face(mirrored), and hybrid(projective), and they allow users to manipulate the spatial layout by which they see other users, thus enhancing workspace awareness. Two input modes are also offered, direct mode and projection mode, which allow users to sketch on an interactive board or a private workspace and project the contents onto a shared interactive board. The system was evaluated with 12 participants by comparing three different layout conditions and analyzing the effectiveness of collaboration. The results show that CollaboVR helps express ideas, and most participants preferred the mirrored layout for task completion and partner connection.

Another framework for collaboration in VR is the BIMFlexi-VR [64], a framework for early-stage collaboration in Flexible Industrial building design. It enables collaborative decision-making and facilitates the creation of more efficient and sustainable industrial constructions. It was built in Unity3D. It enables the users to switch between different parameter values efficiently allowing them to view multiple possible designs quickly.

The BIMFlexi-VR framework (Figure 1) links Grasshopper for Rhino's parametric modeling and structural optimization with a collaborative virtual environment developed in Unity3D. This is achieved through RhinoCompute, which runs in the background and is accessed via REST API. The multi-user functionality is implemented with the Photon Networking for Unity (PUN) plugin. The optimal sets of structural parameters obtained at Step 3 of the BIMFlexi workflow, Multi-objective optimization, are included in the input.xml file. The Rhino Compute server and the main Unity3D client must run on the same machine, but the Photon server can be run on the same or a different computer accessible through the local network or in the cloud, enabling collocated and distributed user collaborations [64]. The system was evaluated by comparing it with a desktop-based one. The study was led by two different groups and two different tasks the first one was to try three different structural parameter sets to find the best one, and the second one was about designing an industrial building and maximizing the flexibility of the structure. Four parameters were fixed for that: the ease of use, learning and skills transfer, and collaborative aspects, the VR received higher scores for ease of use and was reflected in the time results. Scores associated with learning and skills transfer were mixed, with a better understanding of the interaction between production and structure in the desktop setup but better visibility of differences between types of construction in BIMFlexi-VR. Collaborative aspects received slightly higher scores in the desktop setup.

Another example of a collaborative Virtual Assembly Environment product design is studied in [65]. The system was built in two phases, the first one is the immersive VR Environment that was built in Unity3D using Virtual Reality Toolkit (VRTK) and SteamVR.The second phase is the collaborative VR environment using Vizible, a virtual reality tool to present 3D models in a collaborative environment which allows the user to create and modify the 3D objects without requiring specific software. Vizible gives access to all devices like Oculus, and HTC Vive...

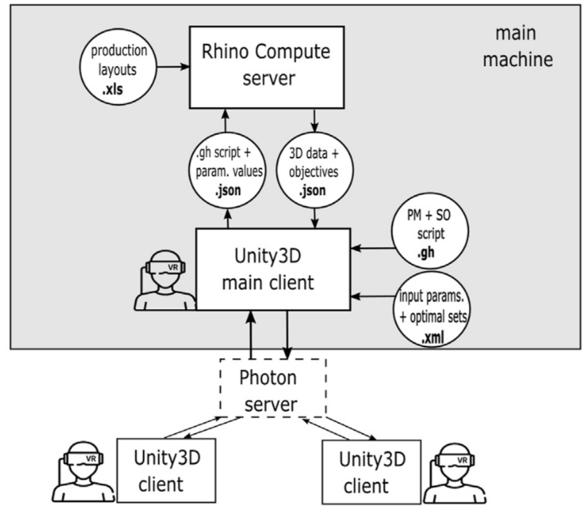

Fig. 1: BIMFlexi-VR framework. Abbreviations: PM, parametric modeling; SO, structural optimization.

In the article [37] The author suggests a notification system called Highlight to draw attention to interactable objects and users, using visual effects such as arrows, radar, and transparent walls. Objects and users are differentiated by color, and a preview feature is proposed to visualize objects in different locations before moving them. The prototype was developed in Unity3D and tested on different devices such as HTC Vive, Oculus Rift, and mobile devices. The evaluation involved testing the prototype with several users using HTC Vive and Oculus Rift devices, divided into two stages. The first stage involved users getting used to the controls and applications without collaborating, while the second stage involved users collaborating in a shared environment. Several types of data were collected, including demographics data, Likert scale inquiries, System Usability Scale (SUS) questionnaire, observations, and user feedback. Overall, 21 tests were conducted with 42 users, and the median age was 23 years old, with a range from 18 to 43. The results showed that object manipulation and locomotion were intuitive, while tool selection mechanisms yielded the worst results.

V. Critical Review of the State of the art

Remote collaborative work has gained more attention in recent years. Several researchers have focused on the collaborative virtual environment because it affords an immersive environment where coworkers can interact and communicate with each other, decreasing the duration of task accomplishment, design errors, and overall costs [66]. In addition to that, It allows quality and efficiency of collaboration among geographically dispersed teams (for example in multinational companies) [67], [68], and between different departments, especially in cases where the real collaboration is difficult, unsafe, or even impossible. However, implementing the collaborative virtual system is still associated with a high cost-to-benefit ratio. Since each user should have an adequate device to access the virtual environment, precisely, each user should have an HMD and an adequate laptop. Additionally, several fundamental choices should be made before building collaborative applications in virtual reality, if all the collaborators have the same accessibility in terms of devices and the actions or roles that they can apply in the collaborative environment. In the context of the management of ships for example, different with different field backgrounds collaborate to prepare the ship, we can ask a technician can change what an electrician did to improve the system from his perspective, or if all the users must access the environment with the same devices and how the user should be represented in the CVE to increase the efficiency of the tasks and the co-presence of the users. And how the user interacts with the virtual object and communicates with each other.

For the first problem, the collaboration could be symmetric where all the users have identical accessibility to the CVE (same devices and same roles), or asymmetric where there is a difference between users either in the devices or in the roles accorded to them. On one hand, Considering the users as the same peers boost the co-presence and allow parallelism in the task excitation [4], [14]. While the asymmetric system can decrease the level of co-presence in some cases like manipulating the virtual objects [4]. However, this is not a general conclusion because, in the context of creative collaborative work [69], the asymmetry is not necessarily negative in terms of its impact on the collaborative work, it facilitated greater efficiency in idea production, while the symmetric collaboration required a clear vision and alignment with objectives to generate high-quality ideas and optimizing drawing time. The asymmetry increases the dependencies situations because not all the users have the same roles, raising the discussion about how we can evaluate the confidence and the communication between the users [69]. One of the benefits of this point is that participants need to communicate with each other which decreases social loafing and promotes teamwork engagement and knowledge sharing [69]. The asymmetric solution gave the ability to use the application on a large scale because it enables non-HMD users to collaborate without the need for an immersive device [70]. The presence of non-HMD users can be increased by sharing the 1st personal scene of HMD users with them.

The choice of the symmetry of the system relies on different circumstances, including the limitations of the team's ability to provide access to technical devices like HMD [69] which force the choice of the asymmetric collaboration, or when there is a disparity of roles and authorities [12], [15].

We can conclude that there is no overall conclusion about the performance of the symmetric and asymmetric collaboration, and the choice depends on several constraints like the nature of the tasks and the difference between the roles assigned to the user group and the device when can afford for the implementation of the experience and the performance of the asymmetric collaboration. To implement asymmetric experience in the industrial context, First, we should identify and assign the roles of each user, since a clear and determined division of roles increases the efficiency of the collaboration process while developing we can compare the results before and after the training of the users to say if there s a difference between the cases [25].

In both symmetric and asymmetric the communication and the interaction between users can be easier and more immersive when there is an avatar that represents each user in the virtual environment [14] When developing a virtual reality collaborative environment several indices should be measured: the presence of the users which is the sense of being present in the virtual environment instead of the physical one. the co-presence means the feeling of being there together. This raises another fundamental question when developing a virtual reality application, in particular, a collaborative virtual reality application. It seems that the choice of representation of the user has an impact on the sense of ownership of the user but not in the collaborative work. Studies show that a sample display of the headset and controllers (or hands) with a floating text indicates the name of each user doesn't impact the collaborative work and is sufficient [71]. And that there is no significant difference between the user's realistic and non-realistic avatar on the task execution [58].

Having said that, a more realistic avatar can increase the sense of ownership of the user [59]. The missing facial expressions can lead to misunderstanding of the intentions [72]. However, the realism of the user representation in the VR Avatar depended on the used technology. [73], it can be limited by technical constraints, the challenge is that the system should be able to track the eyes behind the glasses in the case of eye tracking(eye gaze) of the HMD users. We can also question the importance of realism in the communication between the users, [72]shows that a sample tracking of the eye can increase the realism but still, it can't represent important information such as attention [74]. The absence of important behavioral cues such as eye gaze and facial expression can partly be compensated by the verbal communication between the users for example [75] or by adding sounds for the movement of the user to simulate higher immersion in the context of training with robots [73].

Concerning the graphical representation of the user Some studies shows also that whatever the graphical realism of the avatar the sense of presence is always high in vr with the avatar embodiment [76]and that in many circumstances the user can deal with highly unrealistic avatars or not pay much attention to them [77] Simulating a realistic appearance to achieve high photorealism is expensive and resource consuming [76] and trying to reproduce the physical movement may have a negative impact or wrong results when the movements are different from the reel ones. So, [73]a sample tracked avatar can create a highly expressive representation of another person with more provided information such as display names or different colors to differentiate between users.

To resume in a collaborative immersive environment in some cases like an industrial context the task is one where people should be more focused, they only have to be aware of others' positions and movements in the virtual world instead of focusing on facial expressions. Also, realistic body movement is not required in these cases [78] the users need only to show their presence in the VE. In some cases where the nature of collaboration in social meetings, for example, facial expressions may be important but not in the tasks like industrial design in these cases we can rely on the systems that create facial expressions and eye gaze without mirroring the real user facial expressions [72], and a sample tracking avatar can be sufficient to preserve a high-level presence and co-presence of the users. We can not establish a general conclusion about the choice that should be made, each study case is different from others, in some cases where the facial expressions and eye gaz increase the level of co-presence [61] while in others a sample avatar is sufficient. This choice also should consider the complexity of the tasks assigned to the user to find an optimal representation of the user. One fundamental component of collaboration in general and in virtual reality is communication between users. the VR provides the user with both verbal and non-verbal communication such as voice, facial expression, gesture, and proximity.....Although a lot of studies show that VR gave a better communication experience [32], [61], [79]. Still, there is no general guidance to design social VR applications for better communication nor a summarizing of how to measure the communication in this context [40]. We can invoke here the importance of avatars in the communication between users [80]. Users communicate via their representation in VE both verbally and non-verbally while maintaining a level of privacy [81], [82]. The avatar representation can allow users to reinforce their communication by using body language and being more expressive, depending on the level of its fidelity but the challenge of creating a high-fidelity avatar as we previously discussed. The issue of communication via avatars is that the gap between the real movement and the movement displayed by the avatar leads to misunderstanding and affects the experience so the new challenge at this stage is to reduce the unnatural behaviors of the avatars. In the side of the facial expression and eye gaze which help the users express themselves, the gestures are more important they can besides helping users to express themselves it's also a way to interact with the environment. Proximity is another way to communicate between users how the user's distance from each other reflects their intention and emotions, for example, adding sound doorsteps based on this distance [61].

The experience can be enhanced by adding haptic feedback since it helps increase the quality of the social experience and increases the efficiency of the collaborative work and the level of co-presence [83]–[85]. Another facet of communication between users is the exchange of ideas and data between users. Drawing or sketching in virtual reality can help users to share and discuss their ideas in the virtual environment [61], [85], [86], also displaying the viewport of the user for example to determine the direction of the object the user is staring at and for data sharing VR supports sharing the Media between users in a virtual environment as the case in [87] where the users can share images. To some up VR affords a high immersive quality communication between users, it can reach the same level as face-to-face communication by intruding verbal and non-verbal communication and letting the user feel more and more immersed in the virtual environment [80], [88], [89]. But still the challenge of representing the user and tracking the facial expressions and movement also the need to weary the HMDs that can be heavy not easy to use [80].

One important thing that should be considered in a collaborative virtual environment is object manipulation. Each user needs to be able to manipulate the object based on the roles and the accessibility accorded to him (the accessibility is related also to the choice of the symmetric or asymmetric system as we discussed previously). And also other users should be aware of the modification that occurs. In the asymmetric case when only one user can manipulate a specific object there is no conflict between the users but the question of the way the users should interact with the object arise when more than one user can manipulate the object. To deal with the conflict that may occur in these cases we can rely on making one of the users as a master client who can give ownership of the user who wants to manipulate the object these [26]. In an intuitive technique of manipulating the object in CVE the first person who manipulates the object is the one who can apply changes to that object and all other changes of others are ignored the problem with this technique is that they ignore the quality and the ability of the user to interact (in case for example of moving an object to a specific position and the first user is far from this position or unable to see it well) this technique is simple to use but still the question about the accuracy and the efficiency to be improved. Or by comparing the view Port of each user to determine the one with the best to manipulate the object with as much precision as possible [32], [90]. In some studies, the manipulation of the objects is symmetric means each user can manipulate the same object in the same way as other users the difference between them is the way they combine the modification of each user [38], [38], [39], [91]. Other studies focused more on implementing an asymmetric way for object manipulation by dividing the degree of freedom of the object that each user can manipulate (it's fixed for each task) by providing the user the tools to do so like a global view of the environment [4], [92] The problem with these approaches is it doesn't consider the ability and the efficiency with which the user can manipulate the object also it could be more complex to implement. A lot of studies focused on the other hand on developing more efficient ways to determine the dominant user by improving the calculation of users'viewport [93]. The technique of viewport can be efficient and accurate with a low level of task load and more balanced manipulation between users Also it's proven in [90] that the technique used doesn't affect the user presence nor cause a cybersickness, still a problem with the geometry details that haven't been considered in this technique.

References

[1] Y. Liang and Y. Wang, "Investigation on the influence of virtual reality displays on people's interaction," in *2021 International Conference on Culture-oriented Science & Technology (ICCST)*, pp. 6–10.

[2] Sample understanding virtual reality 2nd 2e | PDF | virtual reality | reality. [Online]. Available: https://www.scribd.com/document/627598744/sample-Understanding-Virtual-Reality-2nd-2E

[3] J. Simard, A. Girard, A. Mayeur, and M. Ammi, "How to improve group performances on colocated synchronous manipulation tasks?" in *2012 IEEE International Workshop on Haptic Audio Visual Environments and Games (HAVE 2012) Proceedings*, pp. 13–18.

[4] J. G. Grandi, H. G. Debarba, and A. Maciel, "Characterizing asymmetric collaborative interactions in virtual and augmented realities," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, pp. 127–135. [Online]. Available: https://ieeexplore.ieee.org/document/8798080/

[5] C. Y. Wang, L. Drumm, C. Troup, Y. Ding, and A. Stevenson Won, "VR-replay: Capturing and replaying avatars in VR for asynchronous 3d collaborative design," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1215–1216, ISSN: 2642-5254.

[6] M. A. Kinsella-Meier and N. M. Gala, "Definitions and explorations of an essential partnership."

[7] J. Lee, P. Quy, J.-I. Kim, L.-W. Kang, A. Seo, and H. Kim, "A collaborative virtual reality environment for molecular biology," in *2009 International Symposium on Ubiquitous Virtual Reality*. IEEE, pp. 68–71. [Online]. Available: http://ieeexplore.ieee.org/document/5232258/

[8] H.-S. Cha, S.-J. Choi, and C.-H. Im, "Real-time recognition of facial expressions using facial electromyograms recorded around the eyes for social virtual reality applications," vol. 8, pp. 62 065–62 075, conference Name: IEEE Access.

[9] J. Klimke and J. Döllner, "Combining synchronous and asynchronous collaboration within 3d city models," in *Geographic Information Science*, S. I. Fabrikant, T. Reichenbacher, M. van Kreveld, and C. Schlieder, Eds. Springer Berlin Heidelberg, vol. 6292, pp. 115–129, series Title: Lecture Notes in Computer Science. [Online]. Available: http://link.springer.com/10.1007/978-3-642-15300-6_9

[10] M. Hosseini and N. Georganas, "MPEG-4 based recording and replay of collaborative virtual reality sessions," in *Proceedings IEEE Virtual Reality 2002*, pp. 271–272, ISSN: 1087-8270.

[11] L. Gericke and C. Meinel, "A document-centric method for combined synchronous and asynchronous applications," in *2013 International Conference on Collaboration Technologies and Systems (CTS)*, pp. 495–502.

[12] N. Feld and B. Weyers, "Mixed reality in asymmetric collaborative environments: A research prototype for virtual city tours," in *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 250–256.

[13] H. Hua, L. D. Brown, and C. Gao, "System and interface framework for SCAPE as a collaborative infrastructure," vol. 13, pp. 234–250.

[14] T. Drey, P. Albus, S. der Kinderen, M. Milo, T. Segschneider, L. Chanzab, M. Rietzler, T. Seufert, and E. Rukzio, "Towards collaborative learning in virtual reality: A comparison of co-located symmetric and asymmetric pair-learning," in *CHI Conference on Human Factors in Computing Systems*. ACM, pp. 1–19. [Online]. Available: https://dl.acm.org/doi/10.1145/3491102.3517641

[15] C. W. Borst, N. G. Lipari, and J. W. Woodworth, "Teacher-guided educational VR: Assessment of live and prerecorded teachers guiding virtual field trips," in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, pp. 467–474. [Online]. Available: https://ieeexplore.ieee.org/document/8448286/

[16] S. Yamamoto, H. Tamaki, Y. Okajima, K. Okada, and Y. Bannai, "Symmetric model of remote collaborative MR using tangible replicas," in *2008 IEEE Virtual Reality Conference*, pp. 71–74, ISSN: 2375-5334.

[17] E. Taylor, "Teaching data warehouses in collaboration with industry :bridging the expectations gap," in *International Conference on Information Society (i-Society 2012)*, pp. 366–369.

[18] J. Goldberg, "Senior design - biomedical engineering/industrial design collaboration in senior design projects," vol. 26, no. 3, pp. 75–76, conference Name: IEEE Engineering in Medicine and Biology Magazine.

[19] W. Pan, D. Yang, F. Li, S. Li, Z. Cheng, and J. Zhang, "Research on large-scale ship 3d design method based on remote cross domain collaboration," in *2023 IEEE 3rd International Conference on Power, Electronics and Computer Applications (ICPECA)*, pp. 612–615.

[20] C. K. Pickering, "Synergizing people, process, and technology to motivate knowledge sharing and collaboration industry case study," in *2013 International Conference on Collaboration Technologies and Systems (CTS)*, pp. 35–39.

[21] I. Hawryszkiewycz, "System requirements for large scale community collaboration," in *2011 International Conference on Collaboration Technologies and Systems (CTS)*, pp. 94–99.

[22] W. Wang, Y. Chai, J. Dong, H. Ding, C. Ren, and M. Qiu, "Evaluating the value of collaboration in supply chain through business process simulation," in *Proceedings of 2011 IEEE International Conference on Service Operations, Logistics and Informatics*, pp. 307–312.

[23] K. Mania and A. Chalmers, "A classification for user embodiment in collaborative virtual environments."

[24] J. N. Bailenson, A. C. Beall, J. Loomis, J. Blascovich, and M. Turk, "Transformed social interaction, augmented gaze, and social influence in immersive virtual environments."

[25] E. F. Churchill and D. Snowdon, "Collaborative virtual environments: An introductory review of issues and systems," vol. 3, no. 1, pp. 3–15. [Online]. Available: http://link.springer.com/10.1007/BF01409793

[26] A. Z. Sampaio, A. R. Gomes, A. M. Gomes, J. P. Santos, and D. P. Rosário, "Collaborative maintenance and construction of buildings supported on virtual reality technology," in *w*, pp. 1–4, ISSN: 2166-0735.

[27] D. Clergeaud, F. Guillaume, and P. Guitton, "3d collaborative interaction for aerospace industry," in *2016 IEEE Third VR International Workshop on Collaborative Virtual Environments (3DCVE)*, pp. 13–15.

[28] Y. Zhang, H. Liu, S.-C. Kang, and M. Al-Hussein, "Virtual reality applications for the built environment: Research trends and opportunities," vol. 118, p. 103311. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0926580520301394

[29] T. C. Peck, H. Fuchs, and M. C. Whitton, "The design and evaluation of a large-scale real-walking locomotion interface," vol. 18, no. 7, pp. 1053–1067. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4091684/

[30] A. Schouten, B. Hooff, and F. Feldberg, *Real Decisions in Virtual Worlds: Team Collaboration and Decision Making in 3D Virtual Worlds.*, journal Abbreviation: ICIS 2010 Proceedings - Thirty First International Conference on Information Systems Publication Title: ICIS 2010 Proceedings - Thirty First International Conference on Information Systems.

[31] Y. P. Gupta, A. Chawla, T. Pal, M. P. Reddy, and D. S. Yadav, "3d networking and collaborative environment for online education," in *2022 10th International Conference on Emerging Trends in Engineering and Technology - Signal and Information Processing (ICETET-SIP-22)*, pp. 1–5, ISSN: 2157-0485.

[32] N. Ali and M. Al-Mhiqani, "Review of virtual reality trends (previous, current, and future directions), and their applications, technologies and technical issues," vol. 12.

[33] P. Wang, P. Wu, J. Wang, H.-L. Chi, and X. Wang, "A critical review of the use of virtual reality in construction engineering education and training," vol. 15, no. 6, p. 1204, number: 6 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: https://www.mdpi.com/1660-4601/15/6/1204

[34] P. Wang, S. Zhang, X. Bai, M. Billinghurst, L. Zhang, S. Wang, D. Han, H. Lv, and Y. Yan, "A gesture- and head-based multimodal interaction platform for MR remote collaboration," vol. 105, no. 7, pp. 3031–3043. [Online]. Available: http://link.springer.com/10.1007/s00170-019-04434-2

[35] M. R. Mine, F. P. Brooks, and C. H. Sequin, "Moving objects in space: exploiting proprioception in virtual-environment interaction," in *Proceedings of the 24th annual conference on Computer graphics and interactive techniques - SIGGRAPH '97*. ACM Press, pp. 19–26. [Online]. Available: http://portal.acm.org/citation.cfm?doid=258734.258747

[36] V. Tanriverdi and R. J. K. Jacob, "Interacting with eye

movements in virtual environments," in *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*. ACM, pp. 265–272. [Online]. Available: https://dl.acm.org/doi/10.1145/332040.332443

[37] V. Pereira, T. Matos, R. Rodrigues, R. Nóbrega, and J. Jacob, "Extended reality framework for remote collaborative interactions in virtual environments," in *2019 International Conference on Graphics and Interaction (ICGI)*, pp. 17–24.

[38] Kai Riege, T. Holtkamper, G. Wesche, and B. Frohlich, "The bent pick ray: An extended pointing technique for multi-user interaction," in *3D User Interfaces (3DUI'06)*. IEEE, pp. 62–65. [Online]. Available: http://ieeexplore.ieee.org/document/1647508/

[39] M. S. Pinho, D. A. Bowman, and C. M. Freitas, "Cooperative object manipulation in immersive virtual environments: framework and techniques," in *Proceedings of the ACM symposium on Virtual reality software and technology*. ACM, pp. 171–178. [Online]. Available: https://dl.acm.org/doi/10.1145/585740.585769

[40] X. Wei, X. Jin, and M. Fan, "Communication in immersive social virtual reality: A systematic review of 10 years' studies." [Online]. Available: http://arxiv.org/abs/2210.01365

[41] S. Aseeri, S. Marin, R. N. Landers, V. Interrante, and E. S. Rosenberg, "Embodied realistic avatar system with body motions and facial expressions for communication in virtual reality applications," in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 580–581.

[42] S. Kimmel, F. Jung, A. Matviienko, W. Heuten, and S. Boll, "Let's face it: Influence of facial expressions on social presence in collaborative virtual reality," in *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*. ACM, pp. 1–16. [Online]. Available: https://dl.acm.org/doi/10.1145/3544548.3580707

[43] K. Suzuki, F. Nakamura, J. Otsuka, K. Masai, Y. Itoh, Y. Sugiura, and M. Sugimoto, "Recognition and mapping of facial expressions to avatar by embedded photo reflective sensors in head mounted display," in *2017 IEEE Virtual Reality (VR)*, pp. 177–185, ISSN: 2375-5334.

[44] J. Lou, Y. Wang, C. Nduka, M. Hamedi, I. Mavridou, F.-Y. Wang, and H. Yu, "Realistic facial expression reconstruction for VR HMD users," vol. 22, no. 3, pp. 730–743, conference Name: IEEE Transactions on Multimedia.

[45] C. G. Fidalgo, M. Sousa, D. Mendes, R. K. d. Anjos, D. Medeiros, K. Singh, and J. Jorge, "MAGIC: Manipulating avatars and gestures to improve remote collaboration." [Online]. Available: http://arxiv.org/abs/2302.07909

[46] D. A. Bowman, E. Kruijff, J. J. LaViola, and I. Poupyrev, "An introduction to 3-d user interface design," vol. 10, no. 1, pp. 96–108. [Online]. Available: https://direct.mit.edu/pvar/article/10/1/96-108/18291

[47] T. Weissker, P. Bimberg, A. Kodanda, and B. Froehlich, "Holding hands for short-term group navigation in social virtual reality," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 728–729.

[48] T. Weissker, P. Bimberg, and B. Froehlich, "Getting there together: Group navigation in distributed virtual environments," vol. 26, no. 5, pp. 1860–1870, conference Name: IEEE Transactions on Visualization and Computer Graphics.

[49] V. Gouranton, T. Duval, and C. Fleury, "A generic model for embedding users' physical workspaces into multi-scale collaborative virtual environments." [Online]. Available: https://www.academia.edu/21267176/A_Generic_Model_for_Embedding_Users_Physical_Workspaces_into_Multi_Scale_Collaborative_Virtual_Environments

[50] W. Robinett and R. Holloway, "Implementation of flying, scaling and grabbing in virtual worlds," in *Proceedings of the 1992 symposium on Interactive 3D graphics*, ser. I3D '92. Association for Computing Machinery, pp. 189–192. [Online]. Available: https://dl.acm.org/doi/10.1145/147156.147201

[51] G. Cirio, M. Marchal, T. Regia-Corte, and A. Lécuyer, "The magic barrier tape: a novel metaphor for infinite navigation in virtual worlds with a restricted walking workspace," in *Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology*. ACM, pp. 155–162. [Online]. Available: https://dl.acm.org/doi/10.1145/1643928.1643965

[52] J. R. Lackner, "Motion sickness: more than nausea and vomiting," vol. 232, no. 8, pp. 2493–2510. [Online]. Available: http://link.springer.com/10.1007/s00221-014-4008-8

[53] T. C. Peck, H. Fuchs, and M. C. Whitton, "Improved redirection with distractors: A large-scale-real-walking locomotion interface and its effect on navigation in virtual environments," in *2010 IEEE Virtual Reality Conference (VR)*, pp. 35–38, ISSN: 2375-5334.

[54] K. Rahimi, C. Banigan, and E. D. Ragan, "Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness," vol. 26, no. 6, pp. 2273–2287, conference Name: IEEE Transactions on Visualization and Computer Graphics.

[55] T. Weissker, A. Kunert, B. Frohlich, and A. Kulik, "Spatial updating and simulator sickness during steering and jumping in immersive virtual environments," in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, pp. 97–104. [Online]. Available: https://ieeexplore.ieee.org/document/8446620/

[56] V. Chheang, F. Heinrich, F. Joeres, P. Saalfeld, R. Barmaki, B. Preim, and C. Hansen, "WiM-based group navigation for collaborative virtual reality," in *2022 IEEE International Conference on Artificial Intelligence and Virtual Reality (AIVR)*, pp. 82–92, ISSN: 2771-7453.

[57] T. Weissker, A. Kulik, and B. Froehlich, "Multi-ray jumping: Comprehensible group navigation for collocated users in immersive virtual reality," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 136–144, ISSN: 2642-5254.

[58] M. Wirth, S. Gradl, G. Prosinger, F. Kluge, D. Roth, and B. M. Eskofier, "The impact of avatar appearance, perspective and context on gait variability and user experience in virtual reality," in *2021 IEEE Virtual Reality and 3D User Interfaces (VR)*, pp. 326–335, ISSN: 2642-5254.

[59] J. C. Eubanks, A. G. Moore, P. A. Fishwick, and R. P. McMahan, "The effects of body tracking fidelity on embodiment of an inverse-kinematic avatar for male participants," in *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 54–63, ISSN: 1554-7868.

[60] T.-Y. Wang, Y. Sato, M. Otsuki, H. Kuzuoka, and Y. Suzuki, "Effect of full body avatar in augmented reality remote collaboration," in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 1221–1222, ISSN: 2642-5254.

[61] P. Heidicker, E. Langbehn, and F. Steinicke, "Influence of avatar appearance on presence in social VR," in *2017 IEEE Symposium on 3D User Interfaces (3DUI)*. IEEE, pp. 233–234. [Online]. Available: http://ieeexplore.ieee.org/document/7893357/

[62] J. Oh, Y. Kim, T. Jin, S. Lee, Y. Lee, and S.-H. Lee, "[POSTER] avatar-mediated contact interaction between remote users for social telepresence," in *2015 IEEE International Symposium on Mixed and Augmented Reality*, pp. 194–195.

[63] Z. He, R. Du, and K. Perlin, "CollaboVR: A reconfigurable framework for creative collaboration in virtual reality," in

2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), pp. 542–554, ISSN: 1554-7868.

[64] I. Podkosova, J. Reisinger, H. Kaufmann, and I. Kovacic, "BIMFlexi-VR: A virtual reality framework for early-stage collaboration in flexible industrial building design," vol. 3, p. 782169. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frvir.2022.782169/full

[65] K. M. Saleem, M. Iqbal, H. Saadi, A. Fatima, and R. N. Enam, "Collaboration of virtual reality in our professional life," in *2019 International Conference on Information Science and Communication Technology (ICISCT)*. IEEE, pp. 1–4. [Online]. Available: https://ieeexplore.ieee.org/document/8777402/

[66] A. Schäfer, G. Reis, and D. Stricker, "A survey on synchronous augmented, virtual and mixed reality remote collaboration systems." [Online]. Available: http://arxiv.org/abs/2102.05998

[67] J. Lacoche, N. Pallamin, T. Boggini, and J. Royan, "Collaborators awareness for user cohabitation in co-located collaborative virtual environments," in *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*. ACM, pp. 1–9. [Online]. Available: https://dl.acm.org/doi/10.1145/3139131.3139142

[68] Y. Zhang, H. Nguyen, N. Ladevèze, C. Fleury, and P. Bourdot, "Virtual workspace positioning techniques during teleportation for co-located collaboration in virtual reality using HMDs," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 674–682, ISSN: 2642-5254.

[69] A. Agnès, F. Sylvain, R. Vanukuru, and S. Richir, "Studying the effect of symmetry in team structures on collaborative tasks in virtual reality," pp. 1–9. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/0144929X.2022.2127375

[70] W. de Paula Ferreira, F. Armellini, and L. A. De Santa-Eulalia, "Simulation in industry 4.0: A state-of-the-art review," vol. 149, p. 106868. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360835220305635

[71] T. Hoang, S. Greuter, and S. Taylor, "An evaluation of virtual reality maintenance training for industrial hydraulic machines," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 573–581, ISSN: 2642-5254.

[72] A. Steed and R. Schroeder, "Collaboration in immersive and non-immersive virtual environments," in *Immersed in Media*, M. Lombard, F. Biocca, J. Freeman, W. IJsselsteijn, and R. J. Schaevitz, Eds. Springer International Publishing, pp. 263–282. [Online]. Available: http://link.springer.com/10.1007/978-3-319-10190-3_11

[73] V. Liagkou, D. Salmas, and C. Stylios, "Realizing virtual reality learning environment for industry 4.0," vol. 79, pp. 712–717. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2212827119301398

[74] M. Garau, M. Slater, V. Vinayagamoorthy, A. Brogni, A. Steed, and M. A. Sasse, "The impact of avatar realism and eye gaze control on perceived quality of communication in a shared immersive virtual environment," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, pp. 529–536. [Online]. Available: https://dl.acm.org/doi/10.1145/642611.642703

[75] D. Roth, J.-L. Lugrin, D. Galakhov, A. Hofmann, G. Bente, M. E. Latoschik, and A. Fuhrmann, "Avatar realism and social interaction quality in virtual reality," in *2016 IEEE Virtual Reality (VR)*, pp. 277–278, ISSN: 2375-5334.

[76] J.-L. Lugrin, M. Wiedemann, D. Bieberstein, and M. E. Latoschik, "Influence of avatar realism on stressful situation in VR," in *2015 IEEE Virtual Reality (VR)*, pp. 227–228, ISSN: 2375-5334.

[77] I. Heldal, R. Schroeder, A. Steed, A. Axelsson, M. Spante, and J. Widestrom, "Immersiveness and symmetry in copresent scenarios," in *IEEE Proceedings. VR 2005. Virtual Reality, 2005.* IEEE, pp. 171–178. [Online]. Available: http://ieeexplore.ieee.org/document/1492771/

[78] A. Steed, M. Spante, I. Heldal, A.-S. Axelsson, and R. Schroeder, "Strangers and friends in caves: an exploratory study of collaboration in networked IPT systems for extended periods of time," in *Proceedings of the 2003 symposium on Interactive 3D graphics*. ACM, pp. 51–54. [Online]. Available: https://dl.acm.org/doi/10.1145/641480.641492

[79] A. S. Khalaf, S. A. Alharthi, I. Dolgov, and Z. O. Toups, "A comparative study of hand gesture recognition devices in the context of game design," in *Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*, ser. ISS '19. Association for Computing Machinery, pp. 397–402. [Online]. Available: https://doi.org/10.1145/3343055.3360758

[80] H. J. Smith and M. Neff, "Communication behavior in embodied virtual reality," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, pp. 1–12. [Online]. Available: https://dl.acm.org/doi/10.1145/3173574.3173863

[81] D. Maloney, G. Freeman, and D. Y. Wohn, ""talking without a voice": Understanding non-verbal communication in social virtual reality," vol. 4, pp. 1–25. [Online]. Available: https://dl.acm.org/doi/10.1145/3415246

[82] (1) avatar-mediated communication in social VR: An in-depth exploration of older adult interaction in an emerging communication platform | romina carrasco - academia.edu. [Online]. Available: https://www.academia.edu/87636473/Avatar_Mediated_Communication_in_Social_VR_An_In_depth_Exploration_of_Older_Adult_Interaction_in_an_Emerging_Communication_Platform

[83] L. Fermoselle, S. Gunkel, F. t. ter Haar, S. Dijkstra-Soudarissanane, A. Toet, O. Niamut, and N. v. van der Stap, "Let's get in touch! adding haptics to social VR," in *ACM International Conference on Interactive Media Experiences*, ser. IMX '20. Association for Computing Machinery, pp. 174–179. [Online]. Available: https://doi.org/10.1145/3391614.3399396

[84] S. Seele, S. Misztal, H. Buhler, R. Herpers, and J. Schild, "Here's looking at you anyway! how important is realistic gaze behavior in co-located social virtual reality games?" in *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, ser. CHI PLAY '17. Association for Computing Machinery, pp. 531–540. [Online]. Available: https://doi.org/10.1145/3116595.3116619

[85] M. Ide, S. Oshima, S. Mori, M. Yoshimi, J. Ichino, and S. Tano, "Effects of avatar's symbolic gesture in virtual reality brainstorming," in *32nd Australian Conference on Human-Computer Interaction*. ACM, pp. 170–177. [Online]. Available: https://dl.acm.org/doi/10.1145/3441000.3441081

[86] S. Baker, J. Waycott, R. Carrasco, R. M. Kelly, A. J. Jones, J. Lilley, B. Dow, F. Batchelor, T. Hoang, and F. Vetere, "Avatar-mediated communication in social VR: An in-depth exploration of older adult interaction in an emerging communication platform," in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, pp. 1–13. [Online]. Available: https://dl.acm.org/doi/10.1145/3411764.3445752

[87] Y. Mei, J. Li, H. de Ridder, and P. Cesar, "CakeVR: A social virtual reality (VR) tool for co-designing cakes," in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, ser. CHI '21. Association for Computing Machinery, pp. 1–14. [Online]. Available: https://dl.acm.org/doi/10.1145/3411764.3445503

[88] J. Li, Y. Kong, T. Röggla, F. De Simone, S. Ananthanarayan, H. de Ridder, A. El Ali, and P. Cesar, "Measuring and understanding photo sharing experiences in social virtual reality," in *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, pp. 1–14. [Online]. Available: https://dl.acm.org/doi/10.1145/3290605.3300897

[89] T. J. Tanenbaum, N. Hartoonian, and J. Bryan, ""how do i make this thing smile?": An inventory of expressive nonverbal communication in commercial social virtual reality platforms," in *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, pp. 1–13. [Online]. Available: https://dl.acm.org/doi/10.1145/3313831.3376606

[90] L. Wang, X. Liu, and X. Li, "VR collaborative object manipulation based on viewpoint quality," in *2021 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pp. 60–68, ISSN: 1554-7868.

[91] R. A. Ruddle, J. C. D. Savage, and D. M. Jones, "Symmetric and asymmetric action integration during cooperative object manipulation in virtual environments," vol. 9, no. 4, pp. 285–308. [Online]. Available: https://dl.acm.org/doi/10.1145/586081.586084

[92] M. L. Chenechal, J. Lacoche, J. Royan, T. Duval, V. Gouranton, and B. Arnaldi, "When the giant meets the ant an asymmetric approach for collaborative and concurrent object manipulation in a multi-scale environment," in *2016 IEEE Third VR International Workshop on Collaborative Virtual Environments (3DCVE)*. IEEE, pp. 18–22. [Online]. Available: http://ieeexplore.ieee.org/document/7563562/

[93] S. Otmane, N. Ouramdane-Djerah, and M. Mallem, "Towards a collaborative 3d interaction model for cooperative design in virtual environments," in *2007 11th International Conference on Computer Supported Cooperative Work in Design*, pp. 198–203.