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Exploring Magic Interactions for Collaboration in Virtual Reality Learning Factory

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Abstract

A hands-on curriculum that blends theory and practical skills is essential to teach manufacturing. An integral part of such a curriculum is a learning factory, which allows engineering students to experience the entire manufacturing cycle of a product in a realistic factory environment. In addition to learning the required technical skills, students can practice their collaborative skills and communication via teamwork in a learning factory. With virtual reality (VR), environments can be made using game engines that simulate their real-world equivalents, providing realistic experiences. Compared to traditional remote learning, VR-based learning together with online remote learning is experiential, allows for natural interaction, and is only limited by the capabilities of the hardware running the virtual environments. The cost of VR devices has dramatically reduced with standalone VR devices such as Meta Quest 2, making these devices a compelling option for specialized educational simulations. A VR Learning Factory should support synchronous collaboration of multiple learners in the same environment. This is a critical advantage of using VR, since collaboration is an essential skill for engineers. To maximize this benefit, it is imperative to develop an appropriate VR interaction mode, because it can greatly influence the effectiveness of collaborations. In this research, we explore multi-user interaction within the context of the VR Learning Factory and compare two modes of virtual user interaction that we call natural and magic. Magic interactions include three additional tools: object container, holographic representation, and multi-object selection. We conduct an analysis of the two modes of VR interaction in a craft production task and show increased performance of using magic interactions.

1. Introduction

Manufacturing helps create wealth, provides jobs, and is vital to the economy. Because technology is changing rapidly, manufacturing companies need to adapt and stay ahead of the competition. There is an imperative need to train future engineers in the manufacturing industries to help them adapt the latest technology to stay competitive. A hands-on curriculum that blends theory and practical skills is needed to teach these essential skills. An integral part of such a curriculum is a learning factory, which is a simulation environment that is designed to provide real-world understanding of how manufacturing systems operate, how they can be optimized, and how they can be maintained. A learning factory may include equipment and tools used in actual manufacturing facilities, such as production lines, assembly stations, and automation systems. Its focus on “active learning” allows participants to apply theory in practical situations and acquire technical and problem-solving skills in a safe and controlled environment. In addition to learning the required technical skills, a learning factory allows engineering students to practice their collaborative skills in teamwork and communication. However, a physical learning factory is extremely costly that requires significant spatial and financial resources. Furthermore, as experienced during the COVID-19 pandemic, access to an in-person learning environment cannot always be guaranteed.

With the advancement of virtual reality (VR) technology, learning factories are no longer limited by physical space and resources but only by the capabilities of the hardware, which is becoming dramatically affordable with standalone VR devices such as the Meta Quest 2. VR enables us to develop virtual learning factories that simulate the entire manufacturing process. This paper presents the VR Learning Factory, which is a simulation environment that aims to provide an interactive and collaborative educational experience for students. VR environments, together with online networking technology, allow us to connect multiple students from different physical locations and place them in the same virtual environment. Students can practice not only technical skills but also collaborative problem-solving skills in a teamwork setting in their learning process. Collaborative learning is an essential part of manufacturing education. Collaboration is an intrinsic characteristic of manufacturing where concepts such as scalability and division of labor are key factors. The multiplayer functionality of the VR Learning Factory facilitates the implementation and extension of collaborative learning in the field of manufacturing. Although VR provides immersive visualization and environment, its interfaces via controllers still have game-like features. An appropriate interaction method is crucial for a VR learning environment to facilitate collaborative simulation and learning.

This research presents and compares two different interaction modes, namely natural and magic. *Natural interaction* simulates how a student would interact with objects in real life – they reach out to objects with their hands, grab them, and pass them to their teammates. However, since this is a virtual environment, other interaction methods can become possibilities. It can feel unnatural and uncomfortable to mimic in a virtual space the way we interact in the real world via controllers. Our alternative interaction mode, which we call *magic interactions*, refers to the ability of students to perform interactions not available in the real life. Students can select, copy, and paste objects within the simulation, which enables them to easily share and duplicate subassemblies or individual objects. They can also see holographic representations of objects to help them with assembly, and select multiple objects at the same time. This research presents our proposed mode of magic interactions, describes its implementation within the VR Learning Factory, and conducts a preliminary usability evaluation to assess the impact of magic interactions on user performance and collaboration. The results of the evaluation indicated that magic interactions indeed improve user performance and collaboration, even though the limited scope of the usability evaluation restricts general conclusions that can be drawn regarding the effectiveness of the magic interactions.

2. Related Research

This section reviews previous research on active, online, and VR-based learning. We also analyze different VR interaction methods. Our objective is to examine prior studies in related areas, analyze their findings, and compare our proposed research. Additionally, this section emphasizes various interaction methods used in previous studies and their impact on collaboration.

2.1 Active Learning

Active learning follows a constructivist approach and emphasizes student engagement and hands-on, collaborative activities. Constructivism proposes that people gain knowledge through practice rather than passive observation. This approach promotes self-reflection and helps students develop the essential skills needed for professional careers [1] Additionally, active learning approaches have decreased failure rates, increased grades [1] [2], and narrowed gaps for underrepresented students [3]. However, implementing active learning strategies in engineering curricula requires extensive time and resources [4]. Despite these challenges, educational institutions have adopted active learning to address the professional skills gap of engineering graduates [5] [6]. These strategies vary from abstracted simulations using consumer goods [7] to complex facilities using specialized equipment [8].

One such implementation of active learning in engineering is the Learning Factory, an integral part of the curriculum developed by the Manufacturing Engineering Education Partnership (MEEP) [8]. The Learning Factory provides engineering students with manufacturing experience closely matching the real world [9]. This approach has been seen to improve knowledge attainment and performance for engineering students over traditional learning methods [9]. However, Learning Factories require many resources to create and maintain; additionally, there are concerns over scalability, specificity, and effectiveness [4]. As a result, researchers have proposed Digital Learning Factories using VR devices to address some of these concerns [10].

2.2 Online-based Learning

Online-based active learning approaches have seen similar success as in-person approaches; additionally, online-based learning provides unique communication methods [11]. VR-based learning engages more senses than traditional online-based learning [12]. These extra senses provide a sense of immersion and presence. The *sense of presence* is the recognition of "being there," while i*mmersion* is the quantitative measure by which technology can simulate a virtual environment [13] [14]. Studies have shown that multisensory integration boosts performance [15] and leads to faster, more efficient learning [16] [17]. These learning environments also provide the ability to integrate artificial intelligence, such as speech recognition [18]. In addition, educators have complete control over the virtual environment, allowing them to simulate scenarios that may not be possible in traditional laboratory or classroom settings.

2.3 VR in Engineering and Manufacturing Education

VR-based learning offers cost-effective, fully interactive, realistic virtual environments that allow students to apply theoretical knowledge to industry problems. VR-based learning integrated closely with course learning objectives offers advantages over traditional learning [19] for engineering students without access to laboratories. As the availability of VR devices increases and the price of VR devices reduces, the availability of VR in engineering education increases. A systematic review study discovered that the primary applications of VR in higher education are to teach: 1) procedural-practical knowledge (33%), such as extinguishing fires, and 2) declarative knowledge (25%), such as memorizing relevant names or concepts [20]. In manufacturing, for example, VR is used to demonstrate safety procedures and operations of machines, such as CAD equipment [21]. In another study, a major Mexican utility company developed a VR maintenance training module for line workers [22]. In many cases, VR is used in limited ways as supplementary materials for teaching static knowledge rather than fully simulating the entire process. Recently, researchers have proposed virtual learning factories that integrate the five manufacturing paradigms [23], and some propose a hybrid learning factory [24] combining the physical and virtual worlds. In addition, integrating gamification elements in the virtual learning factory enhances student engagement [25], and a client-server architecture facilitates multi-user interaction. However, little work has been done to develop interaction methods for multiplayer collaborative learning in manufacturing education.

2.4 VR-based Interaction Modes

This section delves into various interaction methods in VR, focusing on object manipulation and object selection. By exploring the various approaches to interactions in VR, we hope to understand better their impact on collaboration in virtual environments. Natural interaction mimics real-world interaction by mapping a user's actions directly to their virtual representation. As a result, natural interactions in VR devices can increase performance and usability [26]. However, due to technological constraints, VR applications may use semi-natural interactions, which can perform worse than non-natural interactions [26]. In addition, VR is not constrained by physical laws [12], providing the ability to develop interactions not possible in the real world. In VR environments, the ability to interact with objects is crucial, encompassing object manipulation and selection.

2.4.1 Object Manipulation

Object manipulation involves a user interacting with one or more objects allowing them to manipulate the properties of these objects. For networked environments, object manipulation requires mediation when multiple users manipulate a single object. Some techniques mediate movement either asymmetrically or symmetrically between users to accomplish this task. For example, asymmetric techniques assign each user a different role [27], and symmetric techniques allow all users to perform the same movements [28]. Conversely, other manipulation techniques determine which users can manipulate the object through control coordination [29]. Xia et al. proposed a technique that permits fluid object manipulation by creating parallel objects [30]. We examine a hybrid technique that uses control coordination to determine which objects a user can manipulate and provide a way to copy, store, and share objects with other users through a system analogous to cut, copy, and paste systems found in modern graphical user interfaces.

2.4.2 Object Selection

The user's arms' reach limits natural interaction methods for object selection. To improve distant object selection, we can use hyper-natural or magic interaction techniques [31]. For example, VR developers frequently employ ray casting to accomplish this [32]. Ray casting involves casting a virtual ray and checking if it has intersected with an object. We examine a distant object selection system using a discrete ray cast selector. Despite the effectiveness of ray casting, like in the real world, objects in virtual reality can obscure or block the view of other objects making selection difficult [33]. To improve this, techniques that adjust the depth of the ray cast or translate occluded objects have been proposed [33]. Additional techniques have also been proposed that highlight close objects [30] or create miniature worlds [34]. Argelaguet et al. proposed show-through techniques to improve communication in multi-user VR environments [35].

3. Research Framework

The VR Learning Factory is an interactive, multiplayer educational simulation that allows users to build toy cars using plastic brick pieces to meet generated customer orders collaboratively. Utilizing the Unity game engine and Photon Network Library, the virtual environment provides a synchronous multiplayer experience using a room system. The virtual environment comprises five manufacturing rooms, each representing the five manufacturing paradigms: craft production, mass production, lean manufacturing, mass customization, and personalized production [23]. The sixth room is a large storage area for completed toy cars. Through hands-on learning, users assemble toy cars in each of the five rooms, following the specific principles and processes of the corresponding paradigm. In the craft production room, users must assemble toy cars by hand to meet randomly generated customer orders. First, users can choose between two toy car designs and various colors for each part. Then, following the principles of craft production, users must order the correct parts, carefully assemble them, package the assembled toy car, and ensure it is delivered to the customer using their preferred delivery method (Figure 1).

We investigate two interaction modes, natural and magic. Natural interactions mimic real-world interaction by mapping user's actions directly to their virtual representation. For the magic interaction mode, there are three additional tools: object container, holographic representation, and multi-object selection. For object container, users select, copy, and paste objects, and place them in a container, which the user can access at any time. Holographic representation allows users to see where the objects are going to be placed. For multi-object selection, users can pick up multiple objects at the same time using a volumetric selector. Figure 2 shows process flowcharts of assembling a toy car using these interactions.

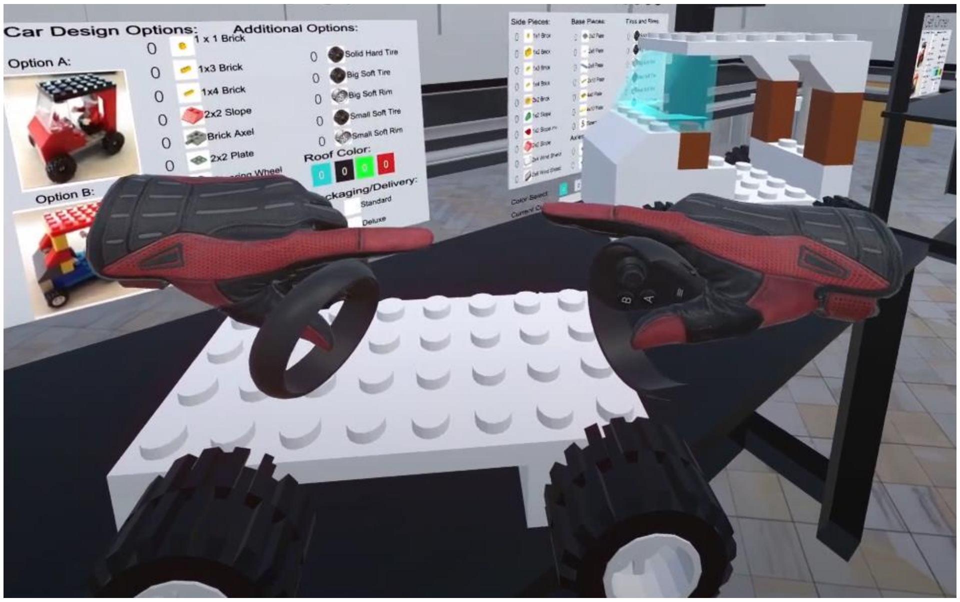


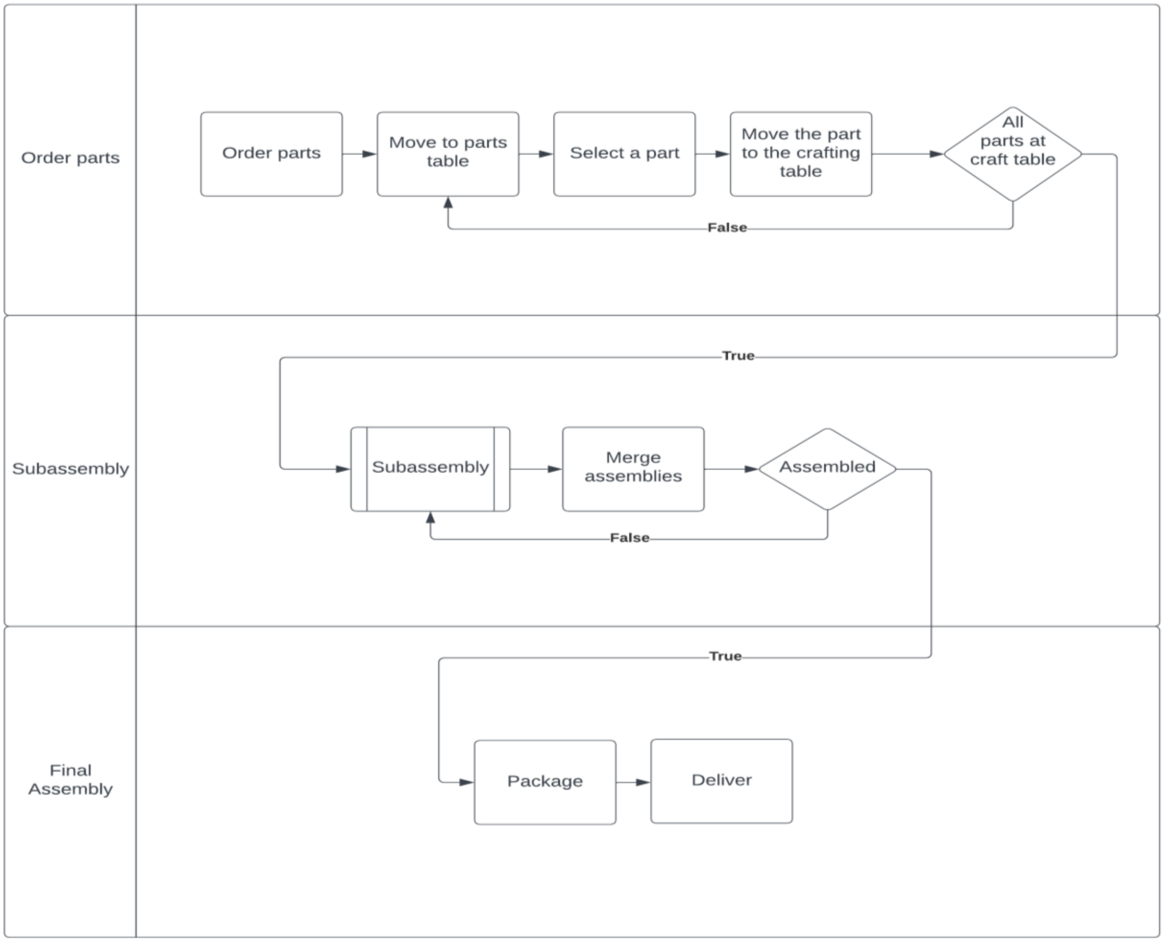
Figure 1. The VR Factory showing what a participant sees when assembling a toy car in the craft production room. Note that although it is not shown in the figure, this is done in collaboration in a four-person team.

3.1 Object Container in Magic Interactions

3.1.1 Object Selection

Using SteamVR's input event system, we developed an input module that manages magic interactions. The input module implements a facade design pattern, providing a simple interface to the complex subsystems. Using this input module, we developed a discrete ray cast tool that allows students to select distant objects. When a user activates the pointer, the input module creates a line renderer from the user's hand. For every update, we check to see if the pointer has intersected with a valid interactable by using a physics ray cast. The pointer color changes to green if the ray cast collides with a valid interactable (Figure 3a). We highlight the collided interactable if the user selects it (Figure 3b).

(a)



Order parts
Order parts
Move to parts table
Select a part
Move the part to the crafting table
All parts at craft table
False
True
Subassembly
Subassembly
Merge assemblies
Assembled
False
True
Final Assembly
Package
Deliver

(b)

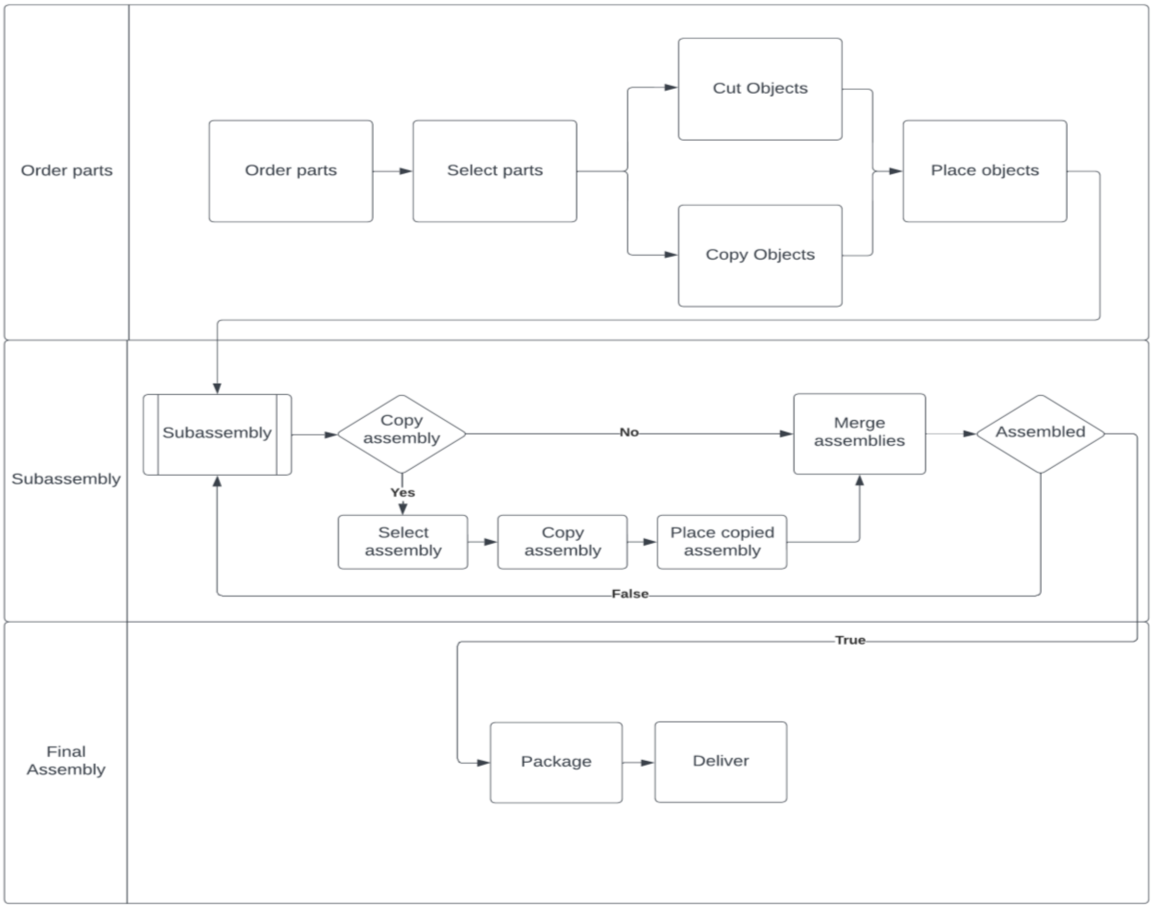
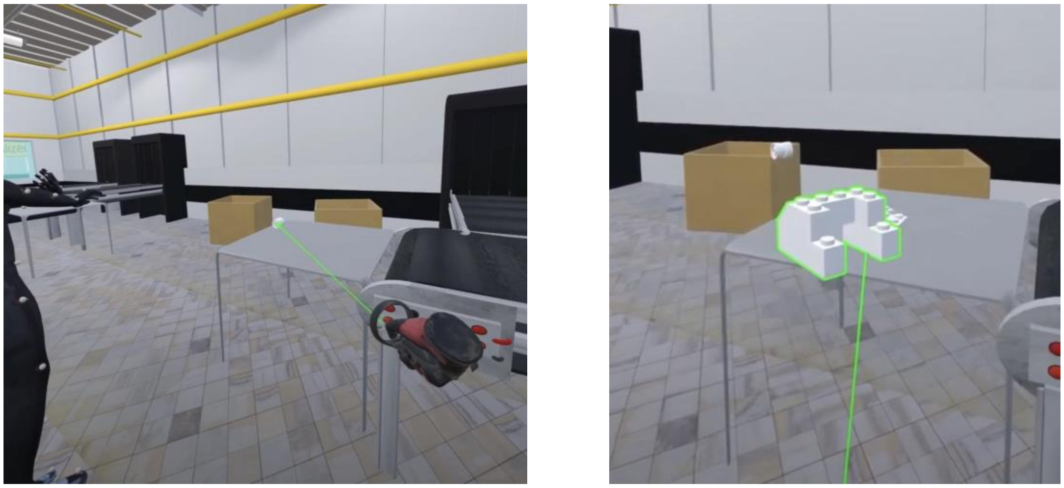
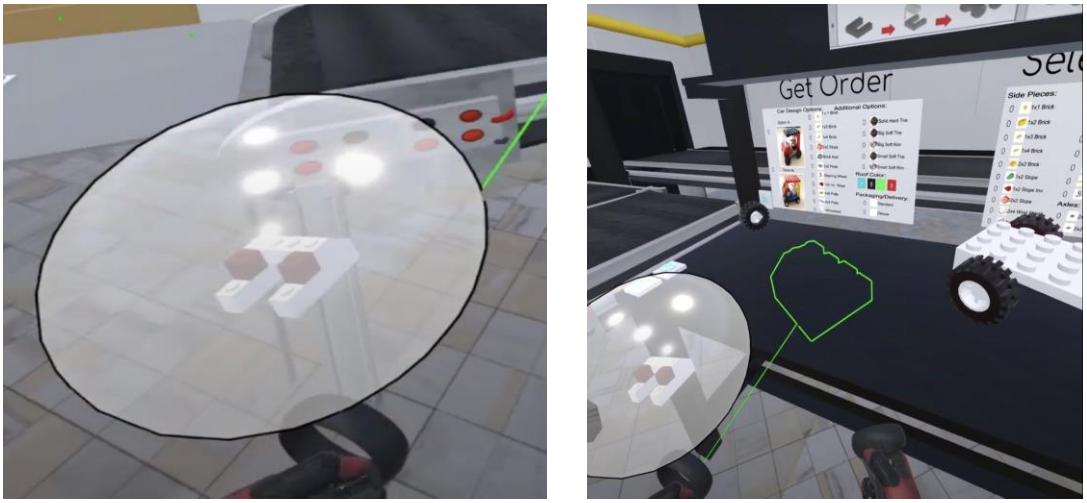


Figure 2. (a) The assembly process for natural interaction, and (b) the assembly process with magic interaction.



(a) (b)

Figure 3. (a) A user pointing at a valid object. (b) A valid object is selected.



(a) (b)

Figure 4. (a) A container with stored objects. (b) A user placing stored objects into the scene.

3.1.2 Object Placement

After selecting the desired objects, users can either cut or copy the objects into a container, which the user can access at any time by pressing a button on their controller. The user can add multiple objects into the container. The container dynamically scales the objects to preserve the relational size between objects (Figure 4a). In addition, the initial copied object sets the local position to zero; further copied objects calculate the relative position from the initial object. These two features provide users contextual-spatial information for multiple stored objects. Finally, when the user is ready, they can place the stored objects into the scene by pressing the A/X button on the Oculus touch controller (Figure 4b). By storing and passing around multiple objects at the same time, magic interactions are set up for more efficient collaborations between team members.

3.2 Holographic Representation in Magic Interactions

To address the issue of object manipulation in the simulation, we implemented several improvements to our interaction mode. Specifically, we introduced object-snapping information and the ability for combined objects to move as one.

Currently, our system uses a grid-snapping function to align placed objects relative to each other. A limitation of this approach is the unpredictability of object placement. To reduce this limitation, we developed a holographic representation of the held object at the calculated snapping position (Figure 5). This green holographic representation gives users a visual indication of where the object will snap to when colliding with another object, making the placement process more predictable and efficient.

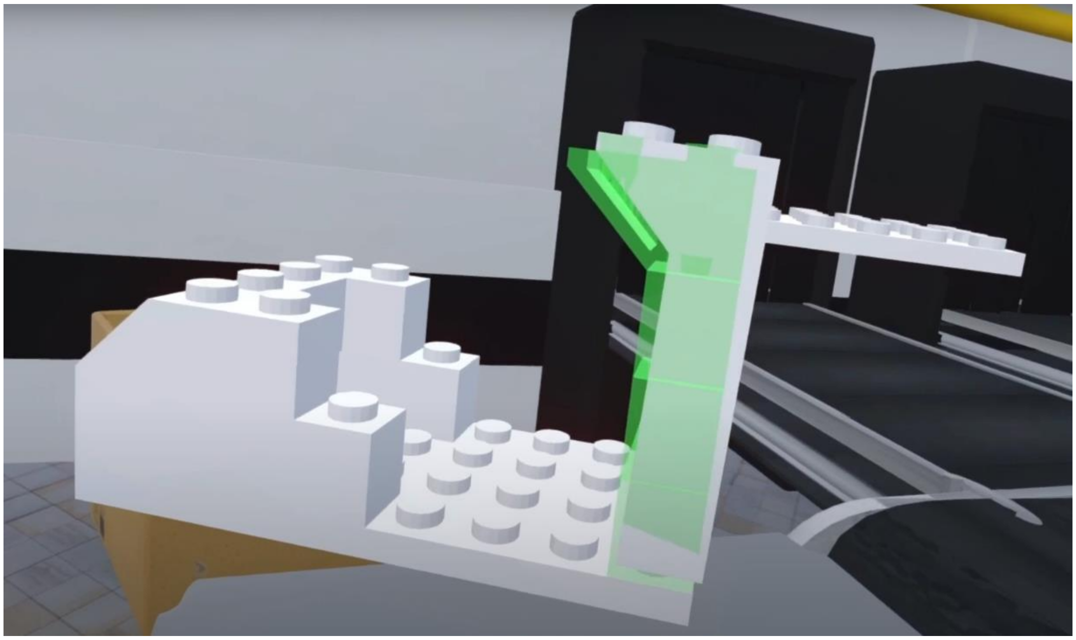


Figure 5. A participant combining two completed subassemblies. The green holographic representation shows the expected location of the object if the user tries to snap the object onto the other.

A few approaches to combining game objects during runtime include creating new assets for each combined object or using Unity's joint component to hold objects together. However, there are better approaches than these for our simulation, as we do not use kinematic objects and require many combined objects that users can break apart.

After careful consideration, we used a parenting approach for object combination. With this approach, child objects can move relative to the parent object, allowing for more flexibility in object manipulation. When a user releases an object, we check for colliding objects and add them to the hierarchy of the released object. We also recalculate the collider of the combined object and add a SteamVR IgnoreHovering component to each child. This way, when the user goes to pick up the combined object, only the parent is selectable, and after pickup, the user can easily pull child objects off the parent. Overall, the parenting approach provides a practical and efficient solution for combining and breaking apart objects in our simulation, allowing a natural approach to building.

3.3 Multi-Object Selection in Magic Interactions

The new building system improves multi-object selection by treating combined objects as a single object. Permitting users to select, copy, and cut finished sub-assemblies as individual objects. We developed a volumetric selector that addresses occlusion issues to enhance object selection further. Unlike the discrete selector, the volumetric selector allows users to select multiple objects simultaneously, even if other objects occlude some objects. When activated, the volumetric selector projects a cone from the user's hand, visually representing the selection zone. A sphere cast from the user's hand collides with any objects within the cone's base diameter (Figure 6). Next, we filter the objects by calculating the object's angle from the user's hand using the following formula: $\theta = \cos^{-1}(\frac{pos_{cone} \cdot pos_{object}}{|pos_{cone}||pos_{object}|})$

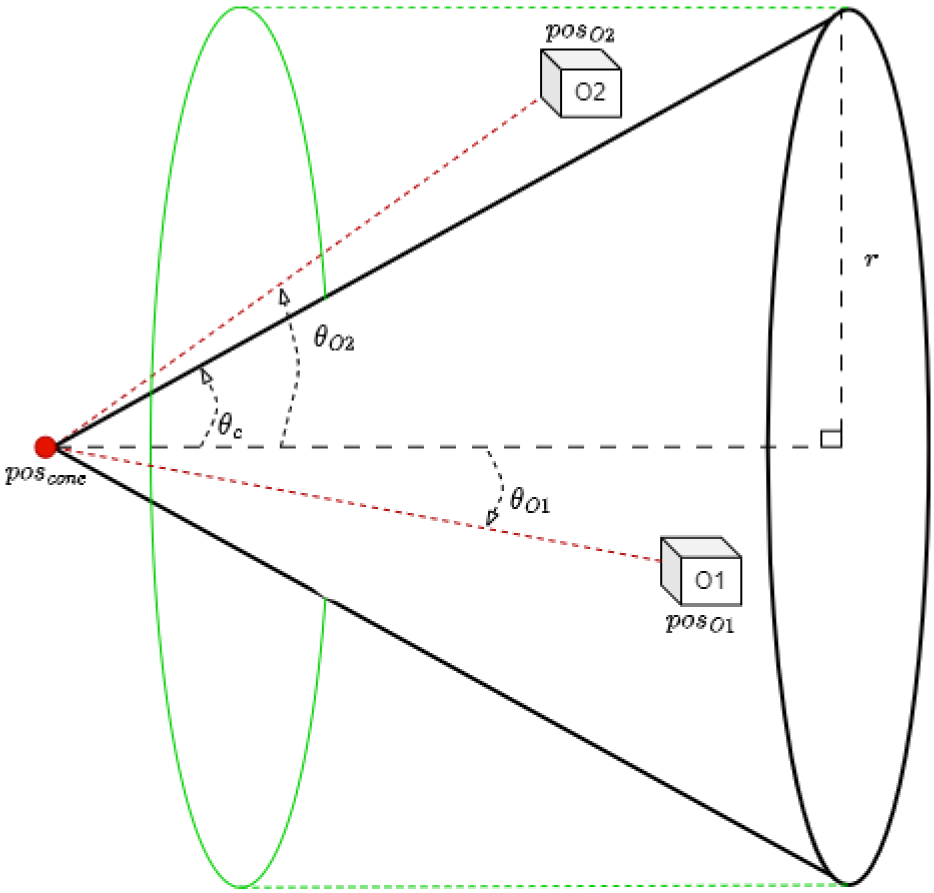


Figure 6. A diagram of the volumetric selector.

Any objects with an angle larger than the closing angle of the cone are filtered out. If an object's angle falls within the selection zone, it is highlighted in green, indicating its selection status. In addition, we have implemented an adjustable size feature to give users greater control over the selection area. By using the analog stick, users can quickly increase or decrease the size of the selection area, allowing for more precise and targeted object selection.

4. Experimental Design and Results

To evaluate and compare these interactions, we conducted a usability evaluation. This evaluation aims to assess each interaction's usability, performance, and collaboration. Four participants remotely joined in the evaluation, each using an HTC Vive, Meta Quest, or Oculus Rift S headset. To assess these interactions, we tasked the participants with assembling toy cars following the principles of craft production. Participants followed the following steps to complete the task:

1. Each participant orders the required parts.
2. A conveyor belt delivers the parts to the parts table.
3. Participants must move their ordered parts from the parts table to their craft table.
4. Each participant assembles the toy car, following the instructions above the craft table.

The assembly task involves participants combining multiple subassemblies into the final product (Figure 7).

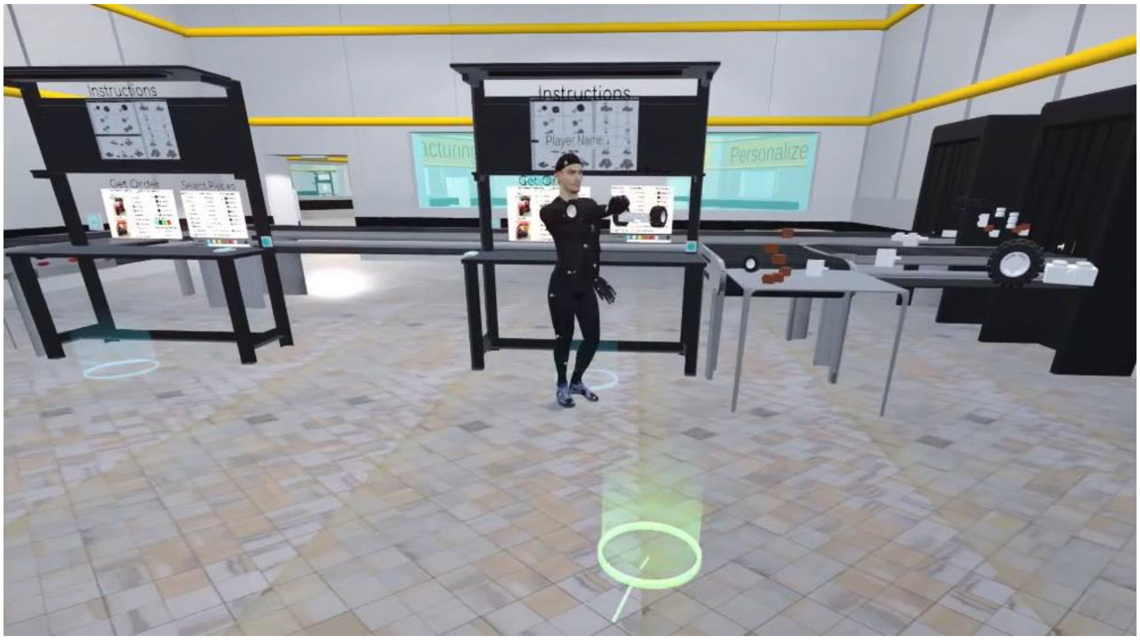


Figure 7. The Virtual Factory showing a participant working at an assembly station.

4.1 Object Container Evaluation

To gather the necessary data, we ran two trials. In the first trial, participants only used natural interaction to complete the task. While in the second trial, participants used the new magic interaction mode we developed, but with only object container enabled. To gauge the effectiveness of each interaction mode on performance, we measured the time to assemble a toy car for each trial. Additionally, we measured the time spent collaborating for each trial (Table 1). For these trials, any time where a participant is helping or working together with another participant, and not directly on the assembly process, is included in the collaboration time data. Examples include assisting another participant in building their assembly and demonstrating how to create one of the subassemblies.

Table 1. Trial results for natural and magic interactions (object container only).

	Natural (min:sec)	Magic – only object container enabled (min:sec)
Assembly Time	14:42.97	10:30.79
Collaboration	2:13.78	2:47.98

Our usability evaluation results suggest that the newly developed magic interaction mode positively impacts user performance in craft production tasks. Additionally, the time spent collaborating was higher for the second trial. Craft production is well suited for the developed magic interactions, as the task heavily relies on object manipulation and selection. For example, participants could duplicate repeated sub-assemblies, reducing repeated trips to receive parts. Furthermore, participants can order a single part and replicate it as many times as necessary, thus reducing the number of parts they need to order. These interactions also provided additional methods of collaborating; for instance, participants could share completed sub-assemblies.

However, the limitation of only being able to select one object at a time hindered the interactions' full potential. We conducted another trial with the volumetric selector enabled, allowing for multi-object selection (detailed in next section). During our evaluation, participants provided feedback on areas for improvement, including the movement of sub-assemblies and the building process. For example, except for the wheels, the sub-assemblies come apart when moved. Additionally, the building process for sub-assemblies was less predictable in VR than in the real world. These factors can significantly impact performance, particularly for those unfamiliar with the process.

Despite these limitations, the participants' feedback highlights the potential for continued improvement and refinement of the interaction methods, including incorporating more natural and predictable building processes and multi-object selection methods. Overall, these findings provide valuable insights into the strengths and weaknesses of the interactions and suggest avenues for future research and development.

4.2 Holographic Representation and Multi-Object Selection Evaluation

To gauge the effectiveness of the holographic representation and multi-object selection, we conducted a sample trial to assess the performance of the assembly task using the updated object manipulation and multi-object selection interactions. This sample trial provides a first look at the impact of the improved interactions on user performance. The results of this trial suggest that the updated interactions significantly improve performance over the Natural and Magic interactions in the previous usability evaluation (Table 2).

Table 2. Trial results for natural and magic interactions.

	Natural (min:sec)	Magic – only object container enabled (min:sec)	Magic – all tools enabled (min:sec)
Assembly Time	14:42.97	10:30.79	05:28.33

The usability evaluation indicates that magic interactions can increase user performance and collaboration. Additionally, the sample trial results suggest that augmenting natural interactions with magic interactions can increase user performance. However, the narrow scope of the usability evaluation and sample trial restricts general conclusions regarding their effectiveness. The results of our study highlight the importance of continuing to explore the impact of different interaction modes on collaboration and performance in a VR Learning Factory setting. In particular, there is a need better to understand the effects of natural interaction modes on performance, as this can help mitigate issues related to unfamiliarity with VR. Additionally, semi-natural and magic interactions may reduce VR-specific issues and improve overall performance and collaboration.

Future research should focus on investigating the effects of these interactions on higher-level collaborative processes, such as mass production, to gain a more comprehensive understanding of their potential benefits. It is also crucial to continue investigating the impact of magic interactions on collaboration and performance. These investigations can inform the development of new and improved interaction modes that further enhance the user experience in VR Learning Factory settings. Overall, continued research and development in this area are essential for advancing the field of VR-based training and improving the effectiveness and efficiency of learning and training processes in the industry and beyond.

5. Conclusions

Collaborative problem solving is an essential skill for engineers. Training students for collaboration is crucial for manufacturing education. With increased deployment of VR for engineering education, effective collaboration between users in VR becomes an important area of research. This research proposes magic interactions, an interaction mode in a VR learning environment that allows for more effective collaborations between users. We compare two different interaction modes, natural and magic, for a VR Learning Factory. The magic interactions allow users to quickly select/copy/paste objects in the VR Learning Factory. These interactions enable users to share and duplicate subassemblies or individual objects. The usability evaluation indicates that magic interactions can increase user performance and collaboration.

Although our initial usability evaluation indicated the potential effectiveness of magic interactions, we recognized the need for further improvements based on feedback from the study participants. As a result, we focused on enhancing the building process through more natural interaction and incorporating additive information to address VR-specific drawbacks. Additionally, we continued to refine the developed magic interactions. A subsequent test showed significant performance improvements, but its narrow scope precludes drawing definitive conclusions.

It is essential to conduct further research on the impact of these interactions on collaboration and performance to continue advancing VR-based learning environments. Our research indicates the critical role of interaction design in creating effective and efficient VR-based learning experiences for learners. Additionally, to fully understand the potential benefits of these interactions, future work should focus on their impact on higher-level collaborative processes, such as mass production. By continuing to investigate and refine these interactions, we can enhance the effectiveness and efficiency of VR-based learning environments, ultimately improving the learning outcomes for engineering students.

References

[1] M. Hernández-de-Menéndez, A. Vallejo Guevara, J. C. Tudón Martínez, D. Hernández Alcántara, and R. Morales-Menendez, “Active learning in engineering education. A review of fundamentals, best practices and experiences,” *International Journal on Interactive Design and Manufacturing*, vol. 13, no. 3, pp. 909–922, Sep. 2019, doi: 10.1007/S12008-019-00557-8.

[2] S. Freeman *et al.*, “Active learning increases student performance in science, engineering, and mathematics,” *Proceedings of the National Academy of Sciences*, vol. 111, no. 23, pp. 8410–8415, Jun. 2014, doi: 10.1073/PNAS.1319030111.

[3] E. J. Theobald *et al.*, “Active learning narrows achievement gaps for underrepresented students in undergraduate science, technology, engineering, and math,” *Proceedings of the National Academy of Sciences*, vol. 117, no. 12, pp. 6476–6483, Mar. 2020, doi: 10.1073/PNAS.1916903117.

[4] M. Tisch and J. Metternich, “Potentials and Limits of Learning Factories in Research, Innovation Transfer, Education, and Training,” *Procedia Manufacturing*, vol. 9, pp. 89–96, Jan. 2017, doi: 10.1016/J.PROMFG.2017.04.027.

[5] V. Jovanovic and M. Tomovic, “A competency gap in the comprehensive design education,” in *ASEE Annual Conference and Exposition*, 2008. doi: 10.18260/1-2--3430.

[6] D. Ellis, G. Liao, and M. Ssemakula, "Closing the Competency Gap in Manufacturing Processes as it Applies to New Engineering Graduates," *Advances in Engineering Education*, vol. 2, no. 1, 2013.

[7] G. Lugaresi, Z. Lin, N. Frigerio, M. Zhang, and A. Matta, "Active Learning Experience in Simulation Class Using A Lego®-Based Manufacturing System," in *Winter Simulation Conference*, Dec. 2019, pp. 3307–3318. doi: 10.1109/WSC40007.2019.9004703.

[8] J. S. Lamancusa, J. E. Jorgensen, and J. L. Zayas-Castro, "The Learning Factory—A New Approach to Integrating Design and Manufacturing into the Engineering Curriculum," *Journal of Engineering Education*, vol. 86, no. 2, pp. 103–112, Apr. 1997, doi: 10.1002/J.2168-9830.1997.TB00272.X.

[9] J. Cachay, J. Wennemer, E. Abele, and R. Tenberg, "Study on Action-Oriented Learning with a Learning Factory Approach," *Procedia-Social and Behavioral Sciences*, vol. 55, pp. 1144–1153, Oct. 2012, doi: 10.1016/J.SBSPRO.2012.09.608.

[10] T. Riemann, A. Kreß, L. Roth, J. Metternich, and P. Grell, "User-oriented Design of Virtual Reality Supported Learning Factory Trainings: Methodology for the Generation of Suitable Design Elements," in *Proceedings of the Conference on Learning Factories*, Jun. 2021. doi: 10.2139/SSRN.3861488.

[11] S. Erickson, C. Neilson, R. O'Halloran, C. Bruce, and E. McLaughlin, "'I was quite surprised it worked so well': Student and facilitator perspectives of synchronous online Problem Based Learning," *Innovations in Education and Teaching International*, vol. 58, no. 3, pp. 316–327, 2020, doi: 10.1080/14703297.2020.1752281.

[12] M. Bricken, "Virtual reality learning environments: potentials and challenges," *ACM SIGGRAPH Computer Graphics*, vol. 25, no. 3, pp. 178–184, Jul. 1991, doi: 10.1145/126640.126657.

[13] J. J. Cummings and J. N. Bailenson, "How Immersive Is Enough? A Meta-Analysis of the Effect of Immersive Technology on User Presence," *Media Psychology*, vol. 19, no. 2, pp. 272–309, Apr. 2015, doi: 10.1080/15213269.2015.1015740.

[14] M. Slater and S. Wilbur, "A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments," *Presence: Teleoperators & Virtual Environments*, vol. 6, no. 6, pp. 603–616, 1997, doi: 10.1162/PRES.1997.6.6.603.

[15] M. Marucci *et al.*, "The impact of multisensory integration and perceptual load in virtual reality settings on performance, workload and presence," *Scientific Reports*, vol. 11, no. 1, pp. 1–15, Mar. 2021, doi: 10.1038/s41598-021-84196-8.

[16] A. R. Rao, "An oscillatory neural network model that demonstrates the benefits of multisensory learning," *Cognitive Neurodynamics*, vol. 12, no. 5, pp. 481–499, Oct. 2018, doi: 10.1007/S11571-018-9489-X.

[17] L. Shams and A. R. Seitz, "Benefits of multisensory learning," *Trends Cognitive Science*, vol. 12, no. 11, pp. 411–417, Nov. 2008, doi: 10.1016/J.TICS.2008.07.006.

[18] J. Suttor, J. Marin, E. Verbus, and M. Su, “Implement AI service into VR training,” in *Proceedings of the 2nd International Conference on Signal Processing and Machine Learning*, Nov. 2019, pp. 114–121. doi: 10.1145/3372806.3374909.

[19] M. Soliman, A. Pesyridis, D. Dalaymani-Zad, M. Gronfula, and M. Kourmpetis, “The Application of Virtual Reality in Engineering Education,” *Applied Sciences*, vol. 11, no. 6, p. 2879, Mar. 2021, doi: 10.3390/APP11062879.

[20] J. Radianti, T. A. Majchrzak, J. Fromm, and I. Wohlgenannt, “A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda,” *Computers & Education*, vol. 147, Apr. 2020, doi: 10.1016/j.compedu.2019.103778.

[21] Z. A. Syed *et al.*, “Use of virtual reality tools in an undergraduate mechanical engineering manufacturing course,” in *ASEE Annual Conference and Exposition*, 2017. doi: 10.18260/1-2--29067.

[22] G. Santamaría-Bonfil, M. B. Ibáñez, M. Pérez-Ramírez, G. Arroyo-Figueroa, and F. Martínez-Álvarez, “Learning analytics for student modeling in virtual reality training systems: Lineworkers case,” *Computers & Education*, vol. 151, p. 103871, Jul. 2020, doi: 10.1016/J.COMPEDU.2020.103871.

[23] R. Zhao, F. Aqlan, L. J. Elliott, and H. C. Lum, “Developing a virtual reality game for manufacturing education,” in *Proceedings of the 14th International Conference on the Foundations of Digital Games (FDG)*, Aug. 2019. doi: 10.1145/3337722.3341831.

[24] B. Thiede, N. Mindt, M. Mennenga, and C. Herrmann, “Creating a Hybrid Multi-User Learning Experience by Enhancing Learning Factories Using Interactive 3D-Environments,” in *Proceedings of the 12th Conference on Learning Factories*, Apr. 2022. doi: 10.2139/SSRN.4074712.

[25] A. Suh, C. Wagner, and L. Liu, “Enhancing User Engagement through Gamification,” *Journal of Computer Information Systems*, vol. 58, no. 3, pp. 204–213, Jul. 2018, doi: 10.1080/08874417.2016.1229143.

[26] R. P. McMahan, C. Lai, and S. K. Pal, “Interaction fidelity: The uncanny valley of virtual reality interactions,” in *International Conference on Virtual, Augmented and Mixed Reality*, 2016, pp. 59–70. doi: 10.1007/978-3-319-39907-2_6.

[27] M. Le 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 *IEEE 3rd VR International Workshop on Collaborative Virtual Environments*, Sep. 2016, pp. 18–22. doi: 10.1109/3DCVE.2016.7563562.

[28] M. S. Pinho, D. A. Bowman, and C. M. D. S. Freitas, “Cooperative object manipulation in immersive virtual environments,” in *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, Nov. 2002, pp. 171–178. doi: 10.1145/585740.585769.

[29] L. Wang, X. Liu, and X. Li, “VR collaborative object manipulation based on viewpoint quality,” in *IEEE International Symposium on Mixed and Augmented Reality*, 2021, pp. 60–68. doi: 10.1109/ISMAR52148.2021.00020.

[30] H. Xia, S. Herscher, K. Perlin, and D. Wigdor, “SpaceTime: Enabling fluid individual and collaborative editing in virtual reality,” in *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, Oct. 2018, pp. 853–866. doi: 10.1145/3242587.3242597.

[31] D. A. Bowman, R. P. McMahan, and E. D. Ragan, “Questioning naturalism in 3D user interfaces,” *Communications of the ACM*, vol. 55, no. 9, pp. 78–88, Sep. 2012, doi: 10.1145/2330667.2330687.

[32] K. Pietroszek, “Raycasting in Virtual Reality,” in *Encyclopedia of Computer Graphics and Games*, 2018, pp. 1–3. doi: 10.1007/978-3-319-08234-9_180-1.

[33] Di. Yu, Q. Zhou, J. Newn, T. DIngler, E. Velloso, and J. Goncalves, “Fully-Occluded Target Selection in Virtual Reality,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 26, no. 12, pp. 3402–3413, Dec. 2020, doi: 10.1109/TVCG.2020.3023606.

[34] R. Stoakley, M. J. Conway, and R. Pausch, “Virtual reality on a WIM: interactive worlds in miniature,” in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 1995, pp. 265–272. doi: 10.1145/223904.223938.

[35] F. Argelaguet, A. Kunert, A. Kulik, and B. Froehlich, “Improving co-located collaboration with show-through techniques,” *IEEE Symposium on 3D User Interfaces*, pp. 55–62, 2010, doi: 10.1109/3DUI.2010.5444719.