Board 342: On the Development of Spatial Visual Abilities among STEM Students via Interactive Mixed Reality Modules

Ms. Israa Azzam, Purdue University, West Lafayette

Israa is a Ph.D. student at Purdue University, specializing in digital technologies and control systems. She received her B.S. degree in Mechanical Engineering from Beirut Arab University (BAU) in 2019 and her M.E. degree in Mechanical Engineering from the American University of Beirut (AUB) in 2021, specializing in Robust Control. Israa is a Research Assistant on the National Science Foundation-funded Project "Research Initiation: Developing Spatial Visualization and Understanding of Complex Systems via Interactive Mixed Reality Modules". Israa leads research endeavors focusing on improving cognitive skills through extended reality (XR). Additionally, Israa's contributions extend to integrating control system analysis and design into XR, where she has developed and implemented multiple interactive Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) modules and platforms. These modules have been effectively utilized in mechanical design, training, remote operation, and engineering education. Israa has received recognition for her contributions, including the best poster and presentation awards for her work, the 2024 Bravo Award for Employee Recognition, and induction into the Honor Society of Phi Kappa Phi, placing her among the top 10% of Purdue Graduate students. Her academic journey reflects a commitment to advancing knowledge and contributing to technological innovation in XR control systems. Her professional aspirations include applying for an Assistant Professor position upon completing her Ph.D. This career trajectory aligns with her desire to leverage her accumulated experience and knowledge to mentor and guide emerging talents. A central component of her vision is inspiring and supporting aspiring scholars in pursuing academic and professional excellence, facilitating impactful change within our field.

Dr. Farid Breidi, Purdue University, West Lafayette

Dr. Farid Breidi joined the School of Engineering Technology at Purdue University as an Assistant Professor in Aug 2020. Farid received his B.E. in Mechanical Engineering degree from the American University of Beirut in 2010, his M.S. in Mechanical Engine

Dr. Faisal Aqlan, University of Louisville

Dr. Faisal Aqlan is an Associate Professor of Industrial Engineering at The University of Louisville. He received his Ph.D. in Industrial and Systems Engineering form The State University of New York at Binghamton.

Dr. Jose M Garcia, Purdue University

Dr. Jose M. Garcia-Bravo is currently an Associate Professor for the Mechanical Engineering Technology program where he has a special focus on fluid power (hydraulic systems) research and instruction, additive manufacturing and smart manufacturing using Industrial Internet of Things technologies. Garcia-Bravo received his B.Sc. in Mechanical Engineering from Universidad de Los Andes, Bogota in 2002, His M.Sc. in 2006 and Ph.D. in 2011 from Purdue University.

Paul Asunda, Purdue University, West Lafayette

Paul A. Asunda is an Associate professor of Engineering and Technology Teacher Education. He holds a joint appointment in the College of Education and Purdue Polytechnic Institute. His research interests focus on the changing nature of work and learning with respect to supporting integration of engineering design and computational thinking practices in integrated STEM (iSTEM) disciplines at the K-12 level.

On the Development of Spatial Visual Abilities among STEM Students via Interactive Mixed Reality Modules (Poster Abstract)

Abstract

Spatial visualization, known as spatial-visual ability, is an ability that integrates both visual perception and visual-mental imagery. It permits depicting the mental manipulation of two and three-dimensional objects without employing visual stimulus and thus is crucial in the conceptualization process among STEM students. Research studies show that students with poor spatial-visual skills feel discouraged because they cannot complete tasks that seem easy to their colleagues. This leads students to consider switching to other majors that do not require high spatial-visual abilities and thus negatively affects the students' educational performance and psychological health. Given this issue, this work aims to examine the students' spatial visualization skills development using state-of-the-art Mixed Reality (MR) technology. The goal is to utilize the features and functionalities of MR to design and implement an interactive MR module that allows for developing engineering students' spatial visualization skills, integrate the module into Fluid Power laboratories, and conduct a research study to test and examine the development of the students' reasoning skills. For conducting the study, an interactive fluid power module on hydraulic gripper designs and operations is developed and deployed in an immersive MR setting using the Microsoft-driven platform Mixed Reality Tool Kit (MRTK) for Unity on the HoloLens 2 hardware. The developed module comprises a 10-minute tutorial session and a 25-minute interactive simulation lab on the gripper. The tutorial session introduces students to the manipulation of virtual objects and spatial interactions within an immersive MR environment, preparing them for conducting the sought-after simulation lab. Throughout the simulation lab, students gain the ability to study the design of two hydraulic grippers by visualizing their internal structure, interacting with their subsystems and components through assembly/disassembly processes, and conducting virtual simulations, all of which facilitate the development of students' reasoning skills. Besides evaluating the effectiveness of MR technology in enhancing students' spatial visualization abilities, the study also aims to investigate the impact of MR modules on students' motivation levels toward learning fluid power concepts. Additionally, it explores how students' prior knowledge of the subject affects their learning experiences. Consequently, the significance of this research lies in its investigation of MR as an educational tool to develop students' cognitive spatial thinking and enhance their technical engineering skills, including diagnostic abilities, simulation, problem-solving, and comprehensive perception.

Keywords: Mixed Reality, HoloLens, Spatial Visualization, Engineering, Learning

1. Introduction

Spatial visualization, also known as spatial-visual ability, is a complex process that combines visual perception and mental imagery, enabling individuals to mentally visualize and manipulate three-dimensional (3D) objects [1]. Developing spatial-visual ability is crucial in STEM education, particularly in conceptualization processes involving cognitive thinking and understanding abstract concepts [2]–[4]. Among various scientific fields, engineering disciplines specifically demand a high level of spatial visualization proficiency [2], [5]. Proficiency in designing, generating, and modeling 3D computer-aided design (CAD) layouts of complex systems is vital for success in fundamental engineering courses, many of which rely on spatial abilities [6]. Engineering skills require strong critical thinking and problem-solving abilities, closely linked to generic intelligence and cognitive ability [7]–[9]. The lack of spatial-visual abilities significantly impacts the educational performance of engineering students, where studies indicate that 10% to 20% of students facing challenges in spatial skills struggle to pass their technical courses [10], [11].

Beyond its academic impact, deficient spatial visualization skills also affect students' psychological health [12]. Students possess varying natural abilities, leading to dissatisfaction and frustration, especially among those lacking spatial skills. The variation in perceptual skills may cause students with inadequate spatial abilities to divert from disciplines requiring solid cognitive skills [13], [14]. Addressing the issue of spatial visualization requires further research to explore and assess new teaching methods for improving spatial-visual skills across various engineering disciplines. Therefore, this study aims to investigate the impact of cutting-edge digital technologies, such as Mixed Reality (MR), on enhancing students' spatial skills in the engineering technology discipline. The study introduces MR technology as an immersive spatial visualization tool, exposing students to 3D visualization and object manipulation through interactive MR modules. Additionally, the research aims to evaluate the impact of incorporating MR as a teaching tool on students' learning experiences and their acquisition of engineering concepts.

2. The MR Spatial Visualization Module

2.1. MR Technology: Features and Functionalities

MR technology is recognized as the forthcoming evolution in the human-machine interface [15]. It establishes an immersive, interactive environment that seamlessly integrates digital content with the physical world, allowing users to engage with and manipulate digital objects in real-time within their actual surroundings [16]. MR employs advanced spatial algorithms, including spatial mapping [17], spatial awareness [18], and spatial anchor [19], enabling the spatial overlay of interactive digital content onto the physical world while monitoring the user's physical actions. Due to its distinctive features and capabilities, MR technology has played a significant role in enhancing engineering education, improving engineering training, problem-solving, and overall student learning experiences [20]–[24]. Beyond its educational utility, MR serves as an effective spatial visualization tool. Its interdisciplinary nature enhances its potential to strengthen students' spatial skills through engaging interactive modules that simulate realistic scenarios. Consequently, a compelling MR module centered on hydraulic systems has been developed and integrated into fluid power laboratories to assess the efficacy of this technology in addressing spatial visualization challenges.

2.2.MR Module Implementation

The MR module comprises a 10-minute tutorial session and a 20-minute simulation lab on hydraulic grippers' visualization and assembly. It is developed using Unity software, a cross-platform game engine provided by Unity Technologies [25], employing the Microsoft-driven

Mixed Reality Tool Kit 2 (MRTK2) for Unity, a Microsoft-driven platform [26], and other platforms to create a realistic MR experience.

The required MR scenes are prepared by installing and importing the MRTK 2 packages (MRTK2 Extensions, MRTK2 Foundations, MRTK2 Test Utilities, MRTK2 Tools, etc., into Unity using the Mixed Reality Feature Tool for Unity [27]. After setting the MR scenes, 3D spatial shapes and gripper CAD FBX models developed on SolidWorks are imported into Unity as GameObject assets. Also, Avatar characters serving as virtual agents are developed and imported to provide guidance throughout the module. MR Unity scripts are then written and incorporated into the Unity assets using built-in UnityEngine and MRTK namespaces, like `(UnityEngine.Events),(Microsoft.MixedReality.Toolkit.UI),(Microsoft.MixedReality.Toolkit.Input)`, etc. The developed scripts allow for near and far interactions with virtual assets, like grabbing, rotating, and manipulating MR objects. The scripts also allow spatial mapping, spatial awareness, eye/hand tracking, and user UI controls. The MR module, including the 10-minute tutorial session and 20-minute simulation, is then built and deployed as a Unity application on the holographic device HoloLen2 manufactured by Microsoft.

2.3.MR Module Capabilities

The MR module comprises a 10-minute tutorial session on MR technology followed by a 20-minute simulation lab focused on hydraulic grippers (see Figure 1). The tutorial session serves to familiarize students with MR features and visualization methods, while the simulation lab exposes them to hydraulic grippers' internal structure, assembly, and operation.

The tutorial session encompasses two primary activities: Activity 1, involving Object Manipulation, and Activity 2, centered on Spatial Visualization. Activity 1 aims to introduce students to fundamental manipulation techniques in MR settings, exposing them to MR features and different interaction methods. Students undergo guided instruction in various methods of interacting with virtual objects, including hand gestures, voice commands, spatial anchors, and other MR interaction functions. Upon completing Activity 1, students should be proficient in interacting with virtual objects before moving to Activity 2. In activity two, students encounter six spatial visualization ability questions designed based on the psychometric properties of the Revised Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R) test [28]. Students must answer these questions in an MR setting by visualizing and interpreting the rotation of 3D objects. Each question prompts students to mentally picture the rotation of an orange object based on the animated yellow object and select the correct option from four choices by tapping the corresponding shape. Visual and auditory aids, such as animations, color changes, and voice commands, are employed to enhance the user experience, providing real-time feedback on the correctness of their answers. This activity aims to enhance students' cognitive and spatial reasoning skills, preparing them for the subsequent simulation lab.

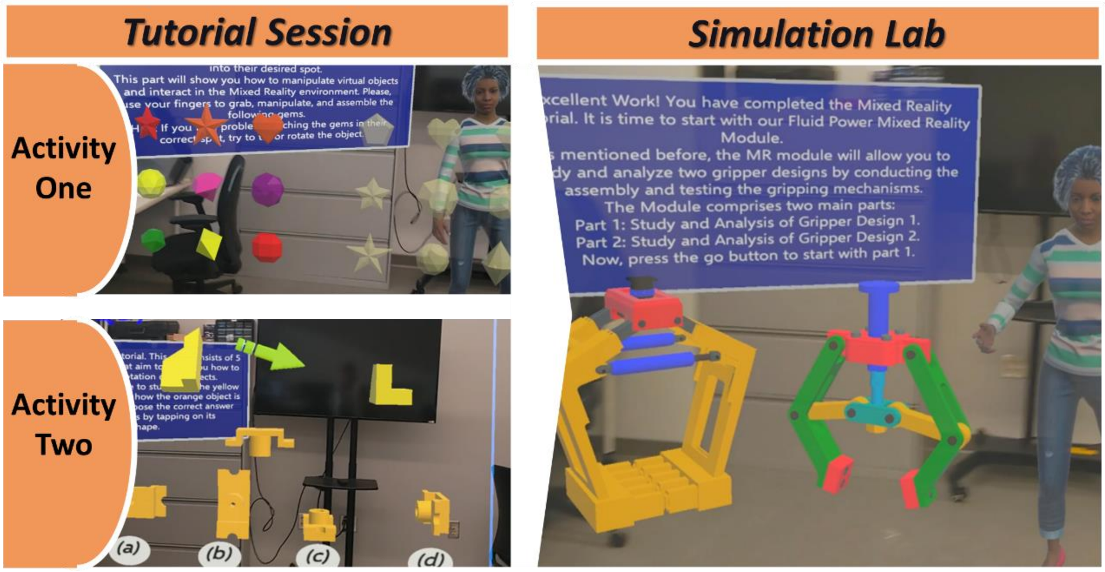

Figure 1. Tutorial Session and Simulation Lab of the MR Module

Following the tutorial, a virtual avatar guides students to the simulation lab, where they engage with two grippers (light-duty and heavy-duty). Three main tasks are assigned for the gripper: Task 1 involves studying the internal structure, Task 2 focuses on assembly generation, and Task 3 entails testing the associated mechanism. Task 1 allows students to interact virtually with the gripper components using the manipulation techniques introduced in the tutorial. Detailed technical information and specifications are presented upon interaction. Task 2 involves assembling the grippers in a predefined sequence, facilitating learning and comprehension of gripper designs. Task 3 permits students to study gripper operation through virtual UI controls, with visual cues such as color changes enhancing the user experience and providing immediate feedback throughout the simulation lab.

3. Research Study

3.1. Experimental Design

The MR module is then integrated into a fluid power course to be experienced by engineering technology students enrolled in the course. Following the approval of an institutional review board (IRB) application, a research study involving 102 students enrolled in the course is conducted. The data collection tool used to assess the students' spatial skill variation employs the Revised PSVT:R and self-reflection surveys. The self-reflection surveys are designed to measure the enhancement in students' spatial skills and to evaluate the students' learning before and after exposure to the MR module. The surveys also measure the students' perspectives regarding MR technology.

The research study occurred for two consecutive weeks, and six MR Microsoft HoloLens2 headsets were used. All the 102 students enrolled in the fluid power course completed the Revised PSVT:R test and then experienced the MR module during one of their lab sessions (see Figure 2). The 102 students in the fluid power course were divided into seven sections, 14 to 15 students per section. As shown in Figure 2, the students in the seven sections were divided into

28 groups (28 experiments), four students per group, to accommodate the number of students. Therefore, 14 experiments have been generated each week in all seven sections. In each experiment, four MR headsets were utilized for the four students who experienced the MR module simultaneously but independently, i.e., each student in their scene. Two weeks after experiencing the MR module, all 102 students who experienced the module re-took the Revised PSVT: R. However, 90 of the 102 students completed the self-reflection survey.

Figure 2. Fluid power students experiencing the MR Module

3.2. Summary of Study Outcomes

The study findings revealed the positive effect of MR technology on enhancing students' spatial abilities. Figure 3 shows that the class average on the Revised PSVT:R test increased from 74% (before MR lab) to 80% (after MR lab). The students' grades on the Revised PSVT:R test showed that approximately 53% of students scored between 80 and 100 before the MR lab. Following their exposure to the MR lab, this percentage increased to 61%, indicating the potential of MR technology to improve the students' spatial abilities. Conversely, before the MR lab, around 20% of students received grades below 60, and this percentage significantly decreased to 8% after students engaged with the MR module. This slight improvement could be further enhanced by exposing students to additional MR labs, allowing them to visualize more complex 3D shapes in MR settings.

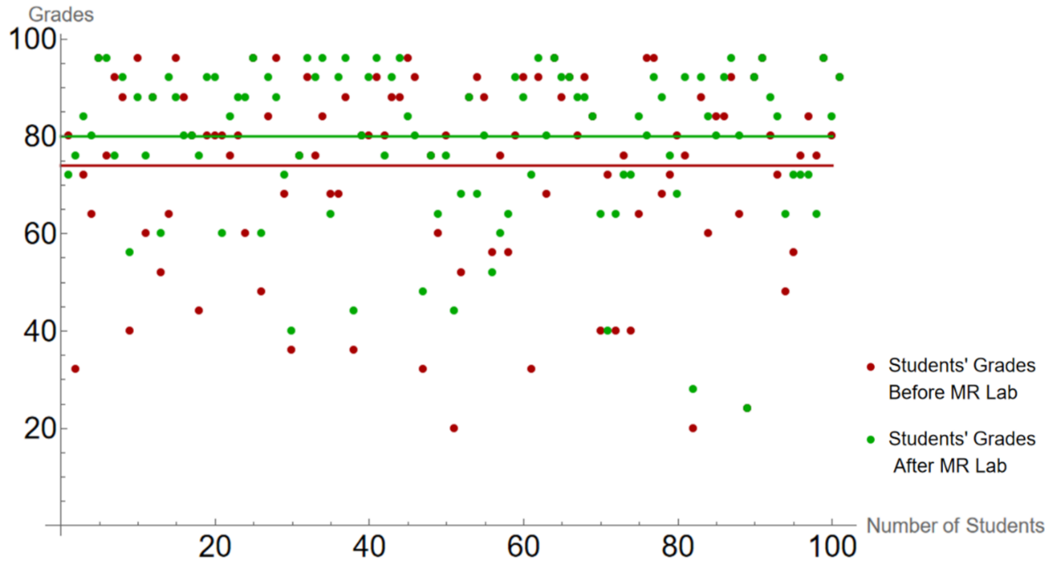

Figure 3. Distribution of students' PSVT:R grades before and after the MR lab

Besides the Revised PSVT:R results, the students' responses on the self-reflection surveys revealed the positive impact of MR on students' overall learning experience, with over 94% of students expressing interest in learning through MR modules. These observations emphasize the MR lab's positive impact on students' performance, contributing to future efforts to utilize advanced technologies to address spatial visualization problems.

4. Conclusions and Future Work

The motivation behind this study is the exploration of MR technology as an instructional spatial tool to foster students' cognitive spatial thinking, strengthening their technical engineering skills, i.e., diagnosis and simulation, problem-solving, and comprehensive perception. Within the scope of this research, an interactive MR module focusing on the design and operation of hydraulic grippers has been developed, leveraging MR functionalities for integration into fluid power courses. A research study has been executed within a fluid power course to assess the impact of MR on students' spatial skills and engineering learning outcomes. The MR module, encompassing a 10-minute tutorial session and a 20-minute simulation lab, was administered to 102 students enrolled in the course. The Revised PSVT:R assessment tool, provided by Purdue University, was employed to evaluate improvements in students' spatial skills. Also, self-reflection surveys were designed and completed by 90 students to analyze improvements in understanding and assess attitudes toward MR technology. The study findings indicated a positive influence of MR technology on enhancing students' spatial abilities, as the class average on the PSVT:R test increased from 74% (pre-MR lab) to 80% (post-MR lab). This slight improvement indicates the potential for further enhancement by exposing students to additional MR labs, enabling them to visualize more complex 3D shapes in MR settings.

Our ongoing work involves designing and implementing shared MR environments to augment collaborative student experiences. The team aims to elevate the MR experience from a single-user to a multi-user interface to reinforce student interactions. The team has achieved the initial milestone in shared MR settings and anticipates testing these advancements in future endeavors through a subsequent research study.

5. References

[1] J. H. Mathewson, “Visual-Spatial Thinking: An Aspect of Science Overlooked by Educators,” *Sci. Educ.*, vol. 83, no. 1, pp. 1098–237, 1999, doi: 10.1002/(SICI)1098-237X(199901)83:1.

[2] G. Duffy, S. Sorby, and B. Bowe, “An investigation of the role of spatial ability in representing and solving word problems among engineering students,” *J. Eng. Educ.*, vol. 109, no. 3, pp. 424–442, Jul. 2020, doi: 10.1002/JEE.20349.

[3] M. Kozhevnikov, M. A. Motes, and M. Hegarty, “Spatial Visualization in Physics Problem Solving,” *Cogn. Sci.*, vol. 31, no. 4, pp. 549–579, Jul. 2007, doi: 10.1080/15326900701399897.

[4] D. Bairaktarova, M. Reyes, N. Nassr, and D. T. Carlton, “Spatial skills development of engineering students: Identifying instructional tools to incorporate into existing curricula.,” in *2015 ASEE Annual Conference & Exposition*, 2015, pp. 26–1389.

[5] R. M. Onyancha, M. Derov, and B. L. Kinsey, “Improvements in Spatial Ability as a Result of Targeted Training and Computer-Aided Design Software Use: Analyses of Object Geometries and Rotation Types,” *J. Eng. Educ.*, vol. 98, no. 2, pp. 157–167, Apr. 2009, doi: 10.1002/J.2168-9830.2009.TB01014.X.

[6] S. Strong and R. Smith, “Spatial Visualization: Fundamentals and Trends in Engineering Graphics CAD Design Graphic Communications Visual Communications Teaching Methods Spatial Visualization: Fundamentals and Trends in Engineering Graphics,” *J. Ind. Technol.* , vol. 18, no. 1, 2001, Accessed: Jan. 15, 2024. [Online]. Available: www.nait.org

[7] C. Charcharos, M. Kokla, and E. Tomai, “Investigating the Influence of Spatial Thinking in Problem Solving,” in *In 19th AGILE International Conference on Geographic Information Science.*, 2016, pp. 1–5. doi: 10.13140/RG.2.1.4186.0729.

[8] D. Van Garderen, “Spatial Visualization, Visual Imagery, and Mathematical Problem Solving of Students With Varying Abilities,” *J. Learn. Disabil.* , vol. 39, no. 6, pp. 496–506, Nov. 2006, doi: 10.1177/00222194060390060201.

[9] Y. S. Allam, “Enhancing spatial visualization skills in first-year engineering students,” Ohio State University , 2010.

[10] C. Brus, L. Zhao, and J. Jessop, “Visual-spatial ability in first-year engineering students: A useful retention variable?,” in *2004 ASEE Annual Conference Proceedings*, 2004, pp. 15361–15373. doi: 10.18260/1-2--13248.

[11] S. Tumkor and R. Harm de Vries, “Enhancing spatial visualization skills in engineering drawing courses.,” in *In 2015 ASEE annual conference & exposition*, 2015, pp. 26–663.

[12] T. Lowrie, T. Logan, and M. Hegarty, “The Influence of Spatial Visualization Training on

Students' Spatial Reasoning and Mathematics Performance," *J. Cogn. Dev.*, vol. 20, no. 5, pp. 729–751, Oct. 2019, doi: 10.1080/15248372.2019.1653298.

[13] D. L. Shea, D. Lubinski, and C. P. Benbow, "Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study," *J. Educ. Psychol.*, vol. 93, no. 3, pp. 604–614, 2001, doi: 10.1037/0022-0663.93.3.604.

[14] S. Titus and E. Horsman, "Characterizing and Improving Spatial Visualization Skills," *J. Geosci. Educ.*, vol. 57, no. 4, pp. 242–254, 2009, doi: 10.5408/1.3559671.

[15] S. Rokhsaritalemi, A. Sadeghi-Niaraki, and S. M. Choi, "A Review on Mixed Reality: Current Trends, Challenges and Prospects," *Appl. Sci.*, vol. 10, no. 2, p. 636, Jan. 2020, doi: 10.3390/APP10020636.

[16] M. Speicher, B. D. Hall, and M. Nebeling, "What is mixed reality?," in *Conference on Human Factors in Computing Systems - Proceedings*, May 2019, vol. 15. doi: 10.1145/3290605.3300767.

[17] "Spatial mapping - Mixed Reality," *Microsoft Learn*, Jan. 31, 2023. https://learn.microsoft.com/en-us/windows/mixed-reality/design/spatial-mapping (accessed Jan. 16, 2024).

[18] "Spatial awareness getting started - MRTK 2," *Microsoft Learn*, Aug. 01, 2022. https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/features/spatial-awareness/spatial-awareness-getting-started?view=mrtkunity-2022-05 (accessed Jan. 16, 2024).

[19] "Spatial anchors - Mixed Reality," *Microsoft Learn*, Mar. 02, 2023. https://learn.microsoft.com/en-us/windows/mixed-reality/design/spatial-anchors (accessed Jan. 16, 2024).

[20] I. Azzam *et al.*, "Design Validation of a Mechanically Actuated Digital Pump Using Mixed Reality Technology.," in *Scandinavian International Conference on Fluid Power (SICFP) Tampere, Finland*, 2023.

[21] I. Azzam, K. Pate, and F. Breidi, "MIXED REALITY TECHNOLOGY: A VIRTUAL TRAINING TOOL IN FLUID POWER ENGINEERING," in *2023 ASME/BATH Symposium on Fluid Power and Motion Control*, 2023.

[22] Y. Jiang, M. Akdere, M. soo Choi, I. Azzam, F. El Breidi, and C. Mousas, "An investigation of the effects of mixed reality on increasing STEM students' career interests in technology on Education in Mathematics, Science and Technology (ICEMST).," in *Nevsehir: Refereed Abstract Book of the International Conference*, 2023, p. 53.

[23] M. Akdere, Y. Jiang, M. soo Choi, I. Azzam, F. El Breidi, and C. Mousas, "Promoting team collaboration in engineering teams through mixed reality technology.," in *The Proceedings Book of the International Engineering and Technology Management Summit.*, 2022.

[24] I. Azzam, K. Pate, F. Breidi, M. Choi, Y. Jiang, and C. Mousas, "Mixed Reality: A Tool for Investigating the Complex Design and Mechanisms of a Mechanically Actuated Digital Pump," *Actuators* , vol. 12, no. 11, p. 419, Nov. 2023, doi:

10.3390/ACT12110419.

[25] "Unity Real-Time Development Platform | 3D, 2D, VR & AR Engine." https://unity.com/ (accessed Apr. 23, 2023).

[26] "MRTK2-Unity Developer Documentation - MRTK 2 | Microsoft Learn," *Microsoft Ignite*, 2022. https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05 (accessed Oct. 03, 2022).

[27] "Welcome to the Mixed Reality Feature Tool - Mixed Reality," *Microsoft Learn*. https://learn.microsoft.com/en-us/windows/mixed-reality/develop/unity/welcome-to-mr-feature-tool (accessed Apr. 23, 2023).

[28] S. Y. Yoon, "Psychometric properties of the revised Purdue Spatial Visualization Tests: Visualization of Rotations (THE Revised PSVT:R)," Purdue University, 2011. Accessed: Jan. 17, 2024. [Online]. Available: http://www.purdue.edu/policies/pages/teach_res_outreach/c_22.html