ICCEPM 2024 https://dx.doi.org/10.6106/ICCEPM.2024.1230
The 10th International Conference on Construction Engineering and Project Management
Jul. 29-Aug.1, 2024, Sapporo

Multi-agent Conversational AI System for Personalized Learning of Construction Knowledge.

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Abstract: Personalized learning is a critical factor in optimizing performance on construction sites. Traditional pedagogical methods often adhere to a one-size-fits-all approach, failing to provide the nuanced adaptation required to cater to diverse knowledge needs, roles, and learning preferences. While advancements in technology have led to improvements in personalized learning within construction education, the crucial connection between instructors' roles and training enviornment to personalized learning success remains largely unexplored. To address these gaps, this research proposes a novel learning approach utilizing multi-agent, context-specific AI agents within construction virtual environments. This study aims to pioneer an innovative approach leveraging the Large Language Model's capabilities with prompt engineering to make domain-specific conversations. Through the integration of AI-driven conversations in a realistic 3D environment, users will interact with domain-specific agents, receiving personalized safety guidance and information. The system's performance is assessed using the five evaluation criteria including learnability, interaction, communication, relevancy and visualization. The results revealed that the proposed approach has the potential to significantly enhance safety learning in the construction industry, which may lead to improve practices and reduction in accidents on diverse construction sites.

Key words: Artificial Intelligence, Virtual Reality, Education, Construction, Personalized Learning.

1. INTRODUCTION AND BACKGROUND

The construction industry, known for its economic significance, consistently faces with the task of balancing high productivity and worker safety. Traditional safety training programs, although essential, often face difficulties in meeting the diverse needs and learning styles of individual workers, leading to knowledge retention gaps, insufficient risk mitigation skills, and avoidable accidents. In this context, personalized learning, a data-driven and learner-centric approach to education, emerges as a promising solution with the potential to revolutionize safety training in the construction industry. Recent research emphasizes the importance of understanding individual learning styles and the transformative power of personalization technologies in education [1], [2]. Researchers in the fields of educational psychology and vocational training have strongly advocated personalization of training experiences over traditional instruction [1], [3]. While advancements in technology have contributed to improvements in personalized learning within construction education, there is still a significant gap in understanding the critical connection between the roles of instructors and the training environment in achieving personalized learning success [4], [5], [6]. The influence of instructors and the design of the training environment on the effectiveness of personalized learning approaches have not been thoroughly explored in the context of the construction industry.

Customized learning environments have been found to enhance the learning experience, particularly in the context of the learning by doing methodology. The sense of presence plays an important role in training effects [7]. A trainee should feel emotionally and cognitively present in the simulated environment in order for their performance to be reflective of the real performance [8]. This is achieved by suspending disbelief by providing an immersive set up that offers a first-person experience to the trainees. The introduction of immersive techniques utilizing virtual and augumented reality solved this problem [9], [10], [11]. However, these systems are usually generic or one-size all fit approaches by introducing the same content with custom delivery methods [12]. These sytems typically use traditional computer inputs for delivery information, which can be challenging for learners with limited technology skills. This may increase the cognitive burden on workers and reduce the effectiveness of the training [13]. The growing maturity of enviornment capture technologies and conversational technologies provides a promising solution to the aformentioned challenges [14]. By offering an authentic learning environment and specific contexts, safety training system can promote situated and contextualized experiential learning [15], [16].

While virtual and 3D BIM simulations offer a realistic feel, they do not fully capture the nature of a real job site [17]. On the other hand, 360 interactive images provide static perspectives and lack complete immersiveness and interaction [9]. However, advanced 3D scanning technologies like gaussain splatting offer dynamic and easily captured interactive environments. Additionally, AI can be leveraged to develop large language models (LLMs) capable of generating human-like responses in real time. Although LLMs like ChatGPT possess extensive knowledge across various domains, their responses may lack relevance in specific contexts [13]. To overcome this challenge, the research proposes the use of prompt engineering techniques to ensure more accurate and effective responses, tailored to the specific requirements of the targeted users. Given these factors, this research presents a bifaced framework as a learning platform to maximize the personalized training perspective. Firstly, it emphasizes the importance of VR-based immersive and trade-specific environments that closely resemble the actual work environment. This aspect aims to fulfill the learning requirements by providing trainees with a realistic experience that aligns with the conditions they will encounter on the job. Secondly, the research introduces multiple LLM-based avatars with specific domain knowledge related to the particular environment or industry being addressed in the safety training system. These avatars serve as virtual guides, delivering content and information according to the individual needs and requirements of the workers. By incorporating these two aspects, the research aims to enhance the effectiveness and personalization of safety training in the construction industry.

The remainder of the paper is organized as follows: Firstly, the research design, encompassing the process and methods employed, is detailed to offer a comprehensive insight into the study. Subsequently, the System Framework and Prototype Development are explored, providing practical insights into the implementation of the proposed approach. The subsequent section evaluates the system, focusing on user experience across four distinct factors. Finally, the paper concludes by discussing the key findings and proposing directions for future research expansion.

2. RESEARCH PROCESS

The research methodology adopted in this study is meticulously structured to address the intricate challenges of personalized learning within the construction knowledge domain. The process initiates with reviewing literature aimed at identifying the existing gaps in the field. This foundational step is pivotal in delineating the specific research objectives, ensuring that the inquiry is grounded in a robust understanding of the current academic discourse and industry practices. Subsequently, the study progresses to the development of a system framework accompanied by a prototype. The basis of this phase is the creation of a context-based virtual scene, which serves as a simulated learning environment for the application of construction knowledge. This immersive virtual space is populated with conversational AI avatars, designed to interact with users and facilitate a dynamic learning experience. The integration of these elements is integrated by a virtual reality platform, which supports the system's architecture and enables a personalized interaction. Following the prototype development, the system evaluation is undertaken. This phase employs the four distinct factors to assess the system's performance, with a specific focus on user experience and workload. Figure 1 presents a step-by-step illustration of the research process that was followed in this study.

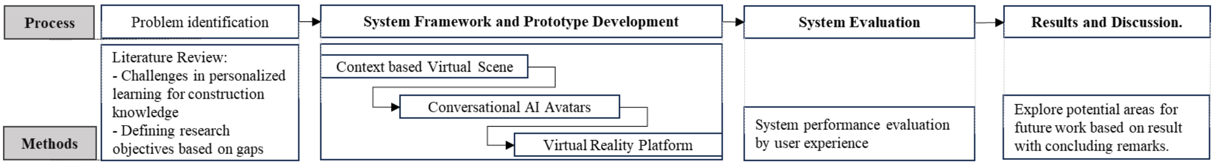

Figure 1: Research Process and Methods

3. SYSTEM FRAMEWORK

The system framework conceptualized in this research represents an innovative combination of a 3D environment database with domain-specific artificial intelligence knowledge, culminating in a customized virtual reality (VR) interface for user interaction. At its core, the framework is designed to embody a multifaceted knowledge repository, encompassing a vast spectrum of vocational trades, each meticulously captured and digitized into a three-dimensional format. The 3D Environment Database serves as the foundational layer, archiving a series of reality-captured scenes that accurately reflect the diverse settings associated with respective trades from construction domain. This particular representation is achieved through advanced reality capture techniques that translate physical spaces into digital twins, allowing for an authentic navigational experience within the VR space. Central to this immersive experience is the AI Avatar, an intelligent entity imbued with domain-specific knowledge across the multitude of trades. This avatar is not merely a guide but an interactive agent capable of delivering tailored responses and guidance, echoing the nuanced understanding of each trade's unique environment and practices.

Figure 2 elucidates this system framework, where the collaboration between the 3D environmental constructs and the AI Avatar's expertise is materialized within the Virtual Reality Environment. This unified space is where users can navigate and interact, guided by the AI Avatar's responsive communication. The interface is designed to recognize voice commands or inquiries released by the user, which the AI Avatar processes to deliver a contextual voice response. This dynamic exchange aims to foster a user experience that is not only responsive but also educational, allowing for a deeper engagement with the subject matter.

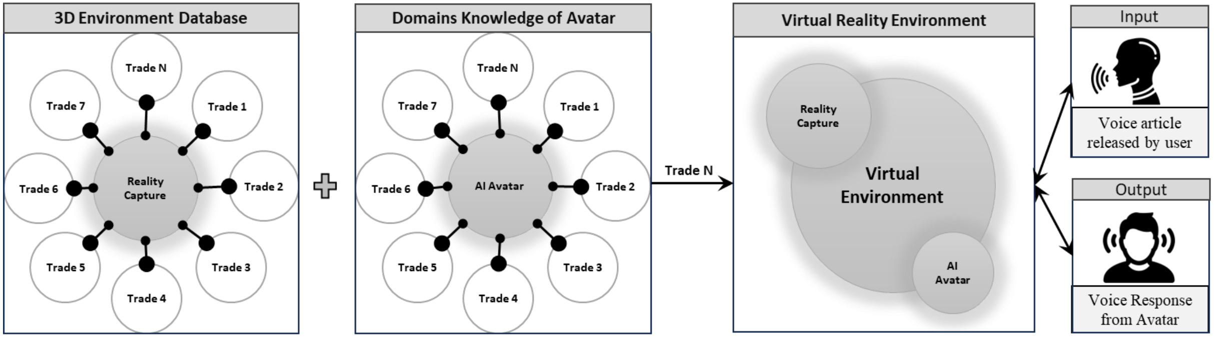

Figure 2: Conceptual Framework for Multi-Agent Personalized Learning System

3.1. Reality Capture for 3D Environment

The systematic approach to translate real-world construction activities and projects into interactive 3D environments is adopted in this module. These environments serve as vital educational tools within the proposed personalized learning framework, offering learners a unique opportunity to engage with their vocational field in a virtual yet palpably realistic setting. At the Activity Level, the process commences with the meticulous capture of the construction site by an industry professional, utilizing sophisticated scanning equipment to collect spatial data. This initial capture is fundamental, as it forms the raw digital canvas upon which the subsequent 3D environment is crafted. The transition from raw spatial data to a refined 3D model is depicted through a sequence of images that chronicle the data's evolution. Initially, we observe what appears to be a point cloud representation, embodying the chaos of unstructured data. This is then artfully processed, as denoted by the 3D Modeling (splattling) stage, where the raw data is methodically organized and transformed into a coherent structural model. The culmination of this process can be illustrated by the detailed 3D model for the indoor activities, where the complexities of the construction environment are vividly brought to life, providing an interactive canvas for learners.

The Project Level follows a similar trajectory but on a substantial scale, encompassing a comprehensive scan of the entire construction project. The initial capture, likely facilitated by both ground and aerial surveying as inferred by the presence of a drone, collects a vast dataset that encapsulates the project's complexity. This dataset undergoes a rigorous 3D Modeling (splattling)'procedure, converging into a detailed and expansive 3D model of the construction site. The final visual in this sequence showcases the model within a specialized software platform, indicating the model's readiness for various applications, including virtual walkthroughs, project review, and immersive educational engagements.

3.2. Interaction with Conversational AI Avatar as Trade-specific Instructor:

The development of a Conversational AI-based Avatar within the Virtual Construction Site framework is a pivotal component of this research, designed to act as a trade-specific instructor. This avatar represents the inclusion of user-centric design and AI-driven pedagogical methodologies, offering an interactive learning journey tailored to personalized learning concept. The interface begins with a dual-input modality, where users, as players or characters, engage through voice or text—this design choice ensures that the system's accessibility extends to a broad demographic, catering to varied preferences and abilities. The incorporation of advanced language processing technologies, akin to the capabilities of ChatGPT, allows for the nuanced interpretation of user inputs, rendering the technology approachable and user-friendly. The architecture of the system is particularly important in its selection of work trade feature, as highlighted in Figure 4. Users are provided the autonomy to customize their learning trajectory by selecting from an array of vocational domains. This feature informs the AI framework, enabling the avatar to deliver content with a high degree of relevance and personalization. The avatar, as a Conversational AI agent, engages in sophisticated prompt evaluation, processing the user's queries with consideration for the chat history. This reflective processing ensures that the AI's responses are contextually rich and continuity-aware, fostering a learning environment that is both adaptive and cognizant of the learner's journey.

Outputs from the system are delivered in the user's chosen format of text or voice, resonating with diverse learning styles and preferences. The maintenance of a chat history is instrumental in cultivating a personalized educational experience, allowing the AI to track and adapt to the user's evolving understanding and skills. Figure 4 exemplifies the system's capacity to act as a responsive, adaptive instructor, providing users with expertise tailored to their selected trade. This avatar acts not only as a repository of trade-specific knowledge but as a responsive and adaptive instructor, capable of guiding users through the nuanced intricacies of their chosen trades with an unprecedented level of personalization and interactive engagement.

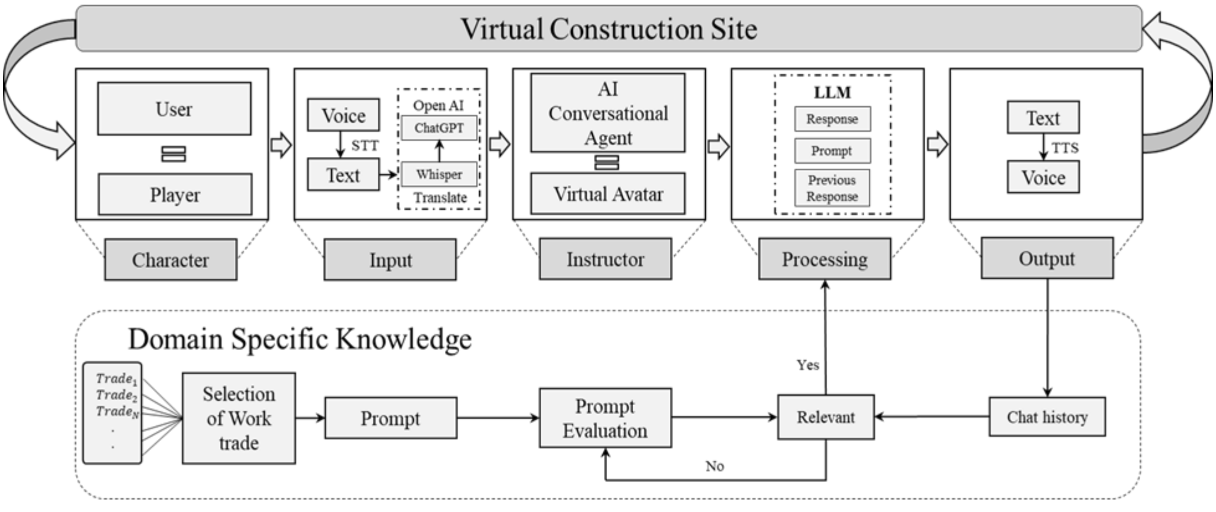

Figure 3: The Systematic flow of LLM integration in virtual enviornments

4. PROTYPE DEVELOPMENT AND SYSTEM EVALUATION

For development of immersive training experience, the 3D mesh created by 3D Gaussain Spallating technique of a construction site in Seoul,South Korea was added. This enviornment provides a realistic representation of a construction site within the virtual setting. Additionally, virtual 3D objects such as simulated construction equipment and objects related to trades were either sourced from the Unity Assets Store [18] or created using Blender 3.5 software. All of these elements were integrated within the Unity game engine (Version: 2021.3.5f1), to create a cohesive and interactive virtual reality training experience. In addition, realistic construction machinery sounds, and site noises were also simulated to replicate the auditory environment of a real construction site.

Avatars sourced from Ready Me Player [19], a flexible library offering customizable virtual characters, were deployed to fulfill distinct roles, encompassing both participants and non-player characters (NPCs) such as instructors and construction workers. To imbue these avatars with lifelike movements, the Unity starter third-person asset was employed, supplemented by open-source Web Maximo animations to simulate a range of worker behaviors including ladder climbing, scaffold walking, and height-related accidents. This integration yielded dynamic and captivating avatar actions within the virtual construction environment. The instructor avatar was seamlessly integrated with OpenAI's extensive language model through C# scripting, facilitating precise and contextually relevant conversations tailored to specific scenarios. Additionally, Oculus Lip Sync technology was leveraged to further enhance immersion by ensuring realistic lip synchronization during participants' interactions with the virtual instructor. The user experience was evaluated through a small-scale experiment conducted at the Construction Technology and Innovation Lab at Chung Ang University. Participants engaged in a carefully crafted scenario involving different work situations, including those with electrical hazards. The system offered a personalized and interactive approach, allowing participants to choose and watch videos tailored to their specific trades.

Figure 4: Participant Site Visit and interaction with Virtual Instructor

To assess the system subjectively, a questionnaire was used, evaluating its performance across five criteria: learnability, interaction, communication, relevancy, and visualization. These criteria were selected based on the study's focus on personalized knowledge delivery, drawing from previous studies for a comprehensive evaluation framework. The questionnaire was distributed to 18 researchers and safety practitioners selected through purposive sampling, ensuring diverse perspectives from individuals with extensive experience in safety education.Participants rated statements on a scale of 1 to 5, indicating their level of agreement or disagreement. For example, a statement related to learnability could be "I find it easier to understand safety protocols using the system compared to traditional methods." These ratings provided valuable insights into participants' perceptions, enabling an evaluation of the system's effectiveness across different criteria. To maintain consistency and comparability, a five-point rating scale was used, as described by Joshi et al. The ratings were recorded for analysis to identify trends and overall scores for each criterion. Additionally, feedback from construction researchers and safety practitioners who experienced the system was collected, enriching the subjective evaluation process with practical insights.The detailed tabled with each evaluation critaria with purpose and benefit of each factor is described in Table 1.

Table 1: Fcators to evaluate system effectiveness

Evaluation Criteria	Purpose and Benefit
Learnability	Facilitate understanding and learning safety protocols compared to traditional methods.
Question: Did the system help you understand and learn safety protocols more effectively than that possible with traditional methods?	
Interaction	Ensure an intuitive and seamless user experience in navigating the virtual environment and interacting with virtual avatars.
Question: Did you find the system to be intuitive for navigating in the virtual environment and interacting with virtual avatars?	
Communication	Facilitate clear and effective communication similar to that of a live instructor.

Question: Did the virtual avatar facilitate clear and effective communication similar to a live instructor?	
Relevancy	Provide relevant answers to users' questions and concerns through the virtual avatar.
Question: Were the answers provided by the virtual avatar relevant to your questions?	
Visualization	Present hazardous scenarios and safety measures effectively through visual representations.
Question: How effectively did the system present visual representation of hazardous scenarios and safety measures?	

5. RESULTS AND EVALUATION

Descriptive statistics were calculated to provide a quantitative overview of the participants' ratings and the variability of their responses for each evaluation criterion. The system received positive ratings across various criteria, with mean scores ranging from 3.67 to 4.30. The highest-rated criterion was interaction, which obtained a mean score of 4.30. This indicated that the system effectively engaged and motivated participants in safety training activities. Relevancy also received relatively high ratings 4.28, highlighting the system's ability to support personalized learning and provide relevant information. However, learnability received a mean score of 3.67 which highlighted the need to enhance the system's ability to facilitate understanding and learning. Interestingly, the system garnered a wide range of scores, with a lower bound of 2.00 and an upper bound of 5.00, suggesting diverse perspectives among the users. Standard deviation values ranged from 0.80 to 0.97, indicating moderate variability in participant ratings across different aspects of system performance. For example, the relatively high standard deviation of 0.97 for learnability implied a wide range of ratings, indicating varying levels of effectiveness of the system in terms of facilitating learning. By contrast, a lower standard deviation of 0.86 for visualization, suggested a more consistent rating pattern for the presentation of hazardous scenarios and construction environment.

These statistics provided a more comprehensive perspective on the evaluation results, showcasing both the strengths and areas for improvement of the developed system. By incorporating these findings into the spider chart, the distribution and dispersion of ratings across the different criteria can be visually depicted (Figure 5), to facilitate quick informative comparison among the evaluation criteria. The results of the evaluation indicate variations in ratings across the practitioners and researchers, and evaluation criteria. The practitioners reported relatively lower learnability scores (2.94) compared to those of researchers (4.31), which suggested that users may need some familiarity to fully grasp the system's functionalities. However, the practitioners rated the system highly in terms of communication (4.44), and visualization (4.31), indicating their positive experiences on these aspects. The researchers, by contrast, rated the system higher on learnability (4.28) and interaction (4.30), suggesting that the system may seem more intuitive and effective to new users. Overall, these results validate the effectiveness and suitability of the developed system in fulfilling its intended purpose.

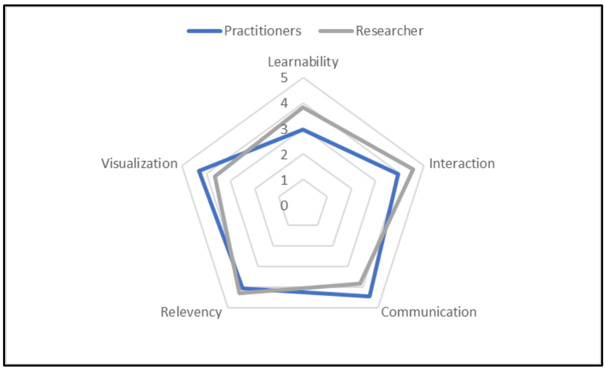

Figure 5: Comparison of Evaluation Criteria Results

These findings contributed to the overall evaluation of the system's effectiveness and its ability to achieve the intended goals. The positive ratings provided by the practitioners suggest that the system was particularly effective at facilitating learning and providing a comfortable user experience to industry related individuals. The positive ratings of the researchers group highlighted the system's effectiveness in supporting their specific needs of communication and relevancy. The findings also provided valuable insights for further improvements and enhancements, to create a more refined and effective system in the future.

6. CONCLUSIONS AND FUTURE WORK

This study has successfully developed and evaluated a systematic framework for personalized safety training in the construction industry by integrating advanced technologies. Through the incorporation of conversational artificial intelligence within a virtual reality system and the unique integration of a 3D reality capture environment, the resulting multi-agent training system offers a novel approach to safety education. Leveraging advanced Large Language Models, the framework can tailor content to the specific needs of users, while the immersive environment enhances the learning experience. The assessment of the system's performance across various criteria underscores its potential to significantly improve safety practices and reduce accidents on construction sites of diverse nature.

Moving forward, future research directions could explore further enhancements and refinements to the proposed framework. One avenue for exploration could involve expanding the scope of the system to incorporate additional safety training modules and scenarios, addressing a broader range of hazards prevalent in the construction industry. Additionally, efforts could be directed towards optimizing the integration of artificial intelligence and virtual reality technologies to create even more interactive and adaptive learning experiences. Furthermore, longitudinal studies could be conducted to evaluate the long-term effectiveness and sustainability of the personalized safety training approach in real-world construction settings. By continuing to innovate and refine this framework, we can further advance safety training practices in the construction industry, ultimately promoting the well-being of workers and the overall success of construction projects.

ACKNOWLEGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. NRF-2022R1A2B5B02002553). This research was conducted with the support of the "National R&D Project for Smart Construction Technology (No.RS-2020-KA156291)" funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport, and managed by the Korea Expressway Corporation.

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