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Real-time Construction Inspection in an Immersive Environment with an Inspector Assistant Robot

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Construction project management requires frequent inspections to ensure the quality and progress of the construction work. Multiple stakeholders are involved in the inspection process during the project lifecycle. Some project stakeholders, such as architects, owners, structural engineers are involved with multiple construction projects at a time and are responsible to conduct timely inspection and monitoring tasks. This paper studies the potential of Virtual Reality (VR) and robotics for real-time remote inspection. The benefits and challenges of using VR for construction inspection and monitoring were identified and ranked through a systematic literature review. The top 5 benefits were found to be enhanced collaboration, realistic and immersive visualization, remote presence, reduction in inspection time, and support for decision-making. The top 5 challenges identified in this study include low-resolution displays, limited integration with existing technologies (such as BIM), causing disorientation and dizziness for the user, cost of adoption, and job site internet access limitations. Finally, a new approach was investigated for using VR to enable an immersive experience in remote inspection with an inspector assistant robot for real-time remote construction inspection. The experimental investigation verified the identified benefits and challenges.

Key Words: construction inspection, legged robots, virtual reality, Spot, quadruped robots

Introduction

Continuous inspection and monitoring provide timely and accurate information about the project, which is essential for successful project completion (Lee et al., 2018). Conventional methods of inspection are time-consuming and require physical presence at the job site (Rahimian et al., 2020). Jaselskis et al., (2015) explored the concept of "telepresence" for real-time monitoring of projects without being present at the site. This remote inspection aims to bring the site to the inspector through various mediums. Studies (Du et al., 2018; Follini et al., 2021; Khan et al., 2021) have used robotics, augmented reality (AR), and virtual reality (VR) for remote inspection. Robotics supports automated data collection from the site that enables remote inspection (K. Asadi et al., 2020). AR and VR provide an intuitive visualization of the collected data (Khan et al., 2021).

This study explores the use of two of these technologies for construction inspection - robot assistants and virtual reality. The main contributions of the study are the identification of the major benefits of using VR for construction inspection, identification of challenges that prohibit the use of VR for

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inspection, and a novel approach of using VR for real-time remote inspection of projects with the help of assistant robots.

In the following sections, the assistant robots are explained briefly. Following that, prior uses of robotics for inspection in the literature are discussed. Later, findings of a systematic literature review on the use of VR for construction inspection and monitoring are presented. The goal of the literature review was to identify the benefits and challenges of using VR for construction inspection. Then, a new approach to integrating VR with robotics is discussed. The proposed approach is further evaluated in an experimental investigation through prototype development and testing. Finally, potential directions for future research are discussed.

Assistant Robots

Assistant robots or mainly collaborative robots work side-by-side with humans and are also referred to as "cobots" (Vysocky & Novak, 2016). Collaborative robots have additional safety requirements (Gambao et al., 2012) that needs to be integrated into their design because they share the workspace with humans. The workspace in which the robot operates is also known as the work envelope (Dritsas et al., 2019). Methods of task execution by assistant robots can be categorized into three categories – a) teleoperated, b) preprogrammed, and c) intelligent systems (Afsari et al., 2018).

Assistant robots, if mobile, use different types of locomotion for navigation through the space (Lattanzi & Miller, 2017). The choice of locomotion depends on the target area of work. For façade inspection, a cable-suspended robot can carry more payload and are safer compared to other types of robots (Barry et al., 2016). For bridge deck inspection, flying robots, also known as, drones or Unmanned Aerial Vehicles (UAV) are more suited (J. et al., 2021). An indoor inspection might be more suited for ground-based robots as UAVs may create additional safety hazards and distractions on the construction site (Khalid et al., 2020). UAVs also have less payload capacity than ground robots (Lattanzi & Miller, 2017). Ground robots may use wheels or crawlers (Lattanzi & Miller, 2017). Wheeled or crawler robots have the inherent limitations of being unable to climb stairs (Afsari et al., 2021). For this, legged robots prove to be advantageous. Legged robots can also walk on rough terrains and unfinished surfaces and over small obstacles which are prevalent on construction sites (Halder et al., 2021).

In an industrial setup, assistant robots support human workers for improving product quality and economic efficiency (Afsari et al., 2018; Vysocky & Novak, 2016). They help isolate workers from unhealthy and hazardous work environments (Vysocky & Novak, 2016).

Robot-enabled Construction Inspection

In construction, assistant robots can be used for inspection (K. Asadi et al., 2018), material handling (Gambao et al., 2012), painting (E. Asadi et al., 2018), etc. Customized robots were designed for research purposes that can augment human capabilities. For example, a cable-crawling robot was used for cable inspection (Sawada et al., 1991). Small micro-bots provide required support for the inspection of small pipes and ducts (Krishna Lakshmanan et al., 2020).

The benefits of using robots for construction inspection are manifold. Purpose-built robots can enable inspection of hard-to-reach places (Katrasnik et al., 2010). They can also isolate human inspectors from hazardous workspaces (Mita & Shinagawa, 2014). Autonomous and intelligent systems can be used to collect information without human intervention and improve productivity (Prieto et al., 2020). Assistant robots can also facilitate remote inspection. Remote inspections are useful for project stakeholders who are located far from the project site and require frequent travel to visit the site (Halder et al., 2021;

Jaselskis et al., 2015). Assistant robots on the site can provide updated information to project stakeholders without additional human support (Follini et al., 2021).

Virtual Reality for Construction Inspection

With increasingly affordable pricing and computational power, Virtual Reality Head-Mounted Displays (HMDs) have become much more accessible to the general public (Sidani et al., 2021). Modern VR HMDs, like Oculus Quest 2 used in this study, use Inertial Measurement Unit (IMU) sensors and cameras to track the position of the user in the given space. In the Architecture, Engineering, Construction, and Operations (AECO) industry, VR has shown many advantages in design reviews, collaboration, and decision making (Sidani et al., 2021). A VR scene can be created from virtual models (Khan et al., 2021) or spherical images (Napolitano et al., 2017). Building Information Modeling (BIM) is often used to create VR scenes (Khan et al., 2021). On the other hand, unlike model-generated scenes which present artificial content, spherical 360° images show the realistic view of the physical site which opens more possibilities for construction inspection as shown in this study.

Methodology

This study used a mixed-methods methodology to study VR and robotics together. First, a systematic literature review was conducted to identify the benefits and challenges of using VR specifically for construction inspection and monitoring. Second, a new approach is proposed to integrate VR with robotics to facilitate a remote immersive inspection by making use of both technologies. The proposed approach was tested qualitatively through experimental investigation to confirm the benefits and challenges identified from the literature review.

The Preferred Reporting of Items for Systematic Reviews and Meta-Analyses (PRISMA) approach used by Sidani et al. (2021) was used for conducting the literature review. Three databases were used to download research papers on the topic of VR for construction inspection. These were a) Web of Science, b) Scopus, and c) Proquest. The search phrase used was: (VR or "Virtual Reality") and construction and (inspection or monitoring). The search fields were the abstract, title, and author's keywords. No filter was applied on the subject or type of source. Figure 1 shows the review process based on the PRISMA approach.

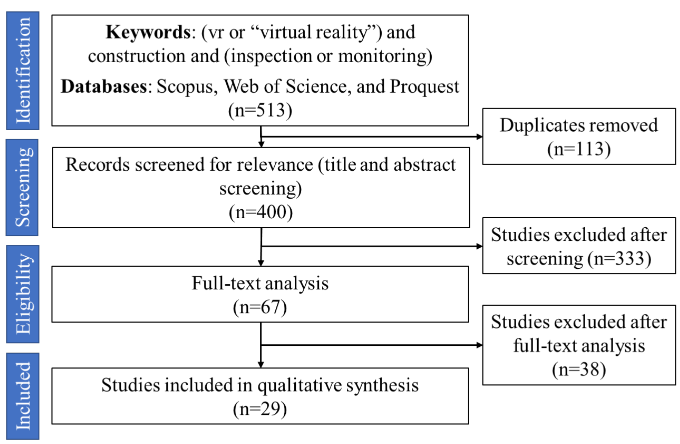

Figure 1. Systematic review process

Total 513 papers were identified from the three sources. After the duplicates were removed, 384 papers remained. Then, the papers were excluded through the review of the title and abstract. Here the papers which were clearly out of the scope of the review were excluded in this step. These were the papers that either used the keywords in the meaning unintended in this review (e.g., VR = Video Recorder) or were from other domains such as medical, mining, or power systems. Papers that used VR for tasks other than inspection or monitoring of construction were also excluded. After this step, 67 papers were remaining on which a full-text analysis was performed. Finally, 29 papers were included in the final qualitative analysis that discussed the benefits and challenges of VR specifically for construction inspection and monitoring. The qualitative content analysis was performed to answer the following research questions:

1. What are the benefits of VR in construction inspection and monitoring?
2. What are the limitations and challenges of VR in construction inspection and monitoring?

Systematic Literature Review Findings

The literature review revealed that VR has been used sparingly for construction inspection and monitoring. Cloud-based VR was found to enhance communication and collaboration by creating a common understanding of a project between remote stakeholders (Du et al., 2018). The immersive visual experience in VR provides a user more realistic experience similar to being present at the site as compared to 2D or 3D models (Attard et al., 2018). Faster navigation in VR than in real-life reduces total inspection time and thereby cost (Omer et al., 2019). Ali et al., (2020) argue that the use of an immersive VR environment for progress monitoring supports decision-making and improves the construction product quality. Figure 2 lists and ranks all the benefits identified from the literature review.

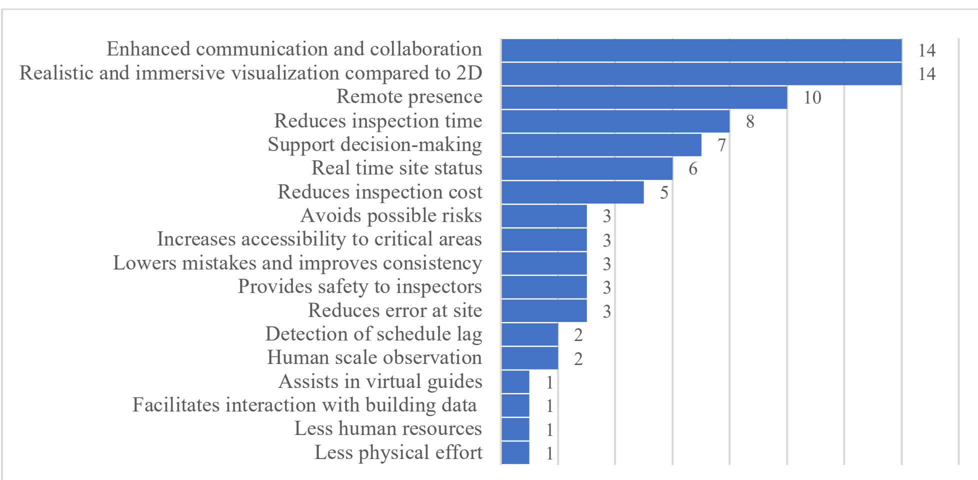

Figure 2. Benefits of VR for construction inspection identified from the literature

Some of the reasons still inhibiting the use of VR for remote construction inspection were identified from the literature. They are listed and ranked in Figure 3. The major limitations identified are the technological limitations. The low resolution of the displays of the existing VR headsets is a limiting factor for inspection because it prevents the user to observe the finer details. Another technical limitation is the juddering effect due to the low refresh rate (Wen & Gheisari, 2020), which is tiring on the eyes of the user. There is also only limited integration with the existing technologies (Sidani et al., 2021). There is a lack of work on creating a real-time data transfer between BIM and VR (Wen &

Gheisari, 2020). The VR development process is also very complex and time-consuming (Wen & Gheisari, 2020).

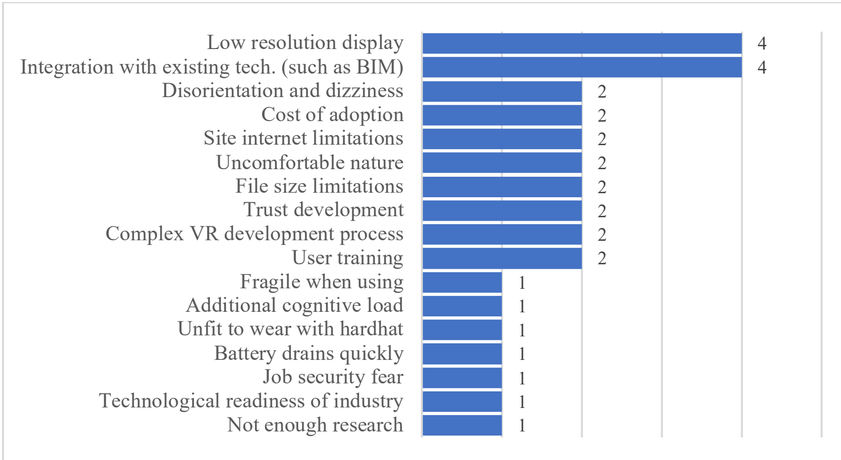

Figure 3. Challenges in using VR for construction inspection identified from the literature

From the literature review, it was found that the content for VR has been predominantly generated from virtual models or prerecorded images and videos. Existing studies have not explored VR with robotics for real-time remote inspection. Robots allow more frequent data capture for construction inspection (Halder et al., 2021). In this research, we conducted an experimental investigation through prototype development and testing to investigate the feasibility of integrating VR with robotics.

Robot-assisted VR for Real-time Remote Inspection

In this section, we propose a new approach to use VR with an inspector assistant robot for real-time remote inspection. The inspector assistant robot is performing remotely on the site to provide real-time remote reality capture while its human operator is located off-site. The approach is based on creating an immersive 3D virtual environment in Virtual Reality where a remote inspector can perform a walkthrough of the building in both reality (through 360° live video feed) and virtuality (through the BIM model). The Unity Engine was used for VR development. The virtual environment was created in Unity by exporting the BIM model from Revit as an FBX file. The hardware included a quadruped robot called Spot by Boston Dynamics with a mounted Ricoh Theta V 360° camera, an Oculus Quest 2 VR headset with its 2 accompanying handheld controllers, and a laptop running a server to interface between devices. All the hardware is connected to the Wi-Fi hotspot hosted from the laptop. Figure 4 shows the schematic diagram of the proposed approach.

The quadruped robot used in this study was the base model of Spot. For more information regarding the fundamentals of quadruped robots, Spot features, standard operating procedure of Spot on construction sites, the accuracy of Spot in construction inspection and monitoring, and BIM-enabled robotic construction inspection and monitoring with Spot, readers are encouraged to review the authors' previous research (Afsari et al., 2021; Halder et al., 2021).

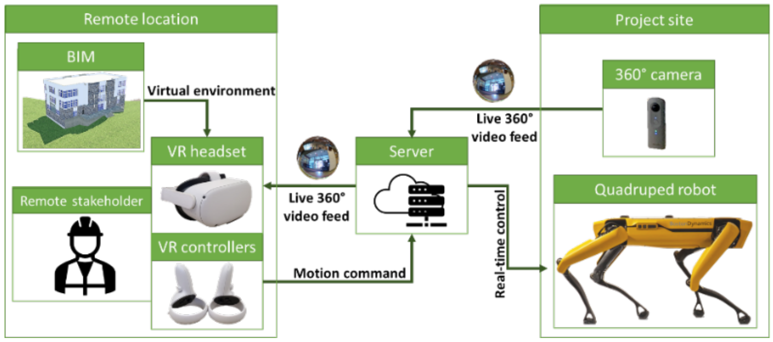

Figure 4. Proposed approach

The live video feed from the 360° camera was applied as texture to a sphere surrounding the virtual camera in the Unity scene at a refresh rate of 20Hz. The VR environment is composed of two components: a virtual environment created from BIM and a 360° live video feed of the remote site from the 360° camera mounted on top of the robot. The user can toggle between the video feed and the BIM model by using one of the hardware buttons in the Oculus controller. The user can also control the robot and navigate it through the space using the joysticks on the controllers of the VR headset (Figure 5).

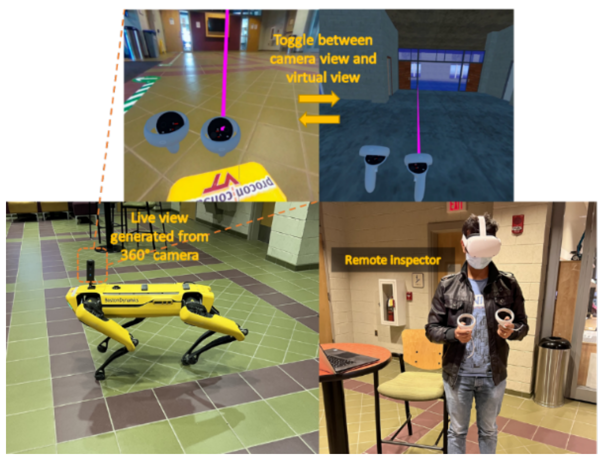

Figure 5. Prototype testing

The proposed approach was validated through experimental testing. The validation focused on the feasibility of the idea and identifying challenges for further improvement of the proposed approach. The main criteria for evaluation were real-time control and the ability to perform the inspection satisfactorily. The research team used the HMD and controlled the robot with the handheld controllers. The robot was walked around in a controlled environment and the area was visually inspected. The observational findings from the experiments are presented below in the next section.

Results and Discussions

The experimental investigation through the developed prototype testing showed the potential of using an inspector assistant robot with Virtual Reality for remote construction inspection and progress monitoring. During the investigation, the robot was directly controlled from the VR environment while the user was looking at the live video feed from the 360° camera on top of the robot. The prototype

provided a real-time and immersive view of the site. Due to the immersive viewing, a closer inspection was possible from the environment. The preliminary testing of the proposed approach of integrating VR with robotics indicated potential benefits from real-time remote inspection of construction, such as remote sense of presence in the space as well as immersive and realistic visualization.
Following technical challenges were faced during the testing:

- Network lag – There were about 1-2 seconds of lag between issuing a motion command and seeing the robot move through the VR headset. This lag can cause potential safety risks in robot navigation.
- Dizziness and discomfort – The VR HMD was found to create discomfort after long use. This can prevent remote inspectors from using the device for longer inspections. However, future improvements in the headsets may partially make them more comfortable.

The experimental testing only focused on identifying the technical challenges and limitations. There can be many managerial challenges as identified from the literature review and presented in Figure 3, such as trust development, training requirements. Future research needs to solve the challenges identified in this study before the benefits of the robot-enabled Virtual Reality inspection can be realized.

Future Directions for Research

VR is an emerging technology and currently available VR headsets have many inherent challenges, such as low-resolution displays. Future studies can investigate the design of lighter and clearer VR headsets for remote inspection. The live VR scene generated from the 360° camera lacked depth information. Stereo cameras or cameras with depth sensors can be used to create 3-dimensional views for VR. Also, in this study, the proposed approach of integrating VR with inspector assistant robots was not investigated with experienced human inspectors. Future studies can conduct human-factors research to study the experience of the inspectors with the proposed immersive environment and to assess the usability and effectiveness of the proposed system. A comprehensive cost analysis is also required to investigate the return on investment (ROI) from the proposed system. Although the robot used in this study was an advanced quadruped robot with relatively high cost, other mobile robots (e.g. legged robots, wheeled robots, or hybrid robots,) might provide more cost-effective solutions.

Conclusion

This study explored robotics and VR for remote construction inspection. Inspection and monitoring is important aspect of construction management. Regular and consistent inspections ensure better project control. Remote inspection capabilities provide a method for remote stakeholders to stay updated about the project's progress and access the project status at any given time. Assistant robots have been used in construction and other industries while these robots work side-by-side with humans and provide support for repetitive and mundane tasks. Assistant robots have the potentials to be used remotely by their human operators to provide remote assistance. VR is another technology that provides immersive visualization of a digitally generated reality known as virtual reality. This virtual reality can be model-generated or can be created from real-life visual data and this study uses a virtual environment that combined the two. In this study, a systematic literature review was conducted on virtual reality for construction inspection and monitoring. After identifying key studies from three databases (Scopus, Web of Science, and ProQuest) using the PRISMA approach, a qualitative analysis was performed on 29 shortlisted papers. The papers were analyzed to identify and rank several benefits and challenges of VR for construction inspection and monitoring. Some of the benefits of using VR are that it provides an immersive and realistic experience as compared to 2D drawings and reports, the intuitive visualization of information enhances communication, and it provides a remote inspector virtual experience close to being physically present at the site, which in turn supports decision-making. There are many challenges for VR to become the primary inspection tool. Some of those challenges are low-resolution displays of the HMDs, lack of strong integration with existing technologies like BIM, the discomfort from long-use of the HMDs, cost of adoption, and site internet limitations. The study also proposed a novel approach to integrating VR with robotics through an experimental investigation using a VR prototype integrated with remote robot control and the identified benefits and challenges were discussed to guide future research.

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