Remote Monitoring System and Controller for the Construction Machinery using AR Smart Glasses

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Abstract –

The increased use of construction machinery in the industry poses challenges of safety and regulation for the site workers. A remote monitoring system for the construction machinery can help in avoiding fatal accidents whilst providing continuous sensor information to the user. The present remote controller has shortcomings of accessibility, less information transfer, longer training times, and sizeable delays in case of replacement. Smart glasses are already a booming trend in the industry in the domain of worker training and there is a need for simultaneously controlling and monitoring machinery using the portable device. A framework is proposed for using the smart glasses to provide network relay of the construction machinery with its digital counterpart by using the concepts of artificial reality and connectivity through the CPS to minimize the problems of safety and communication. The paper summarizes the solution by using a cyber-physical system along with the latest trend of AR (augmented reality) to control unmanned tower cranes on the location using smart glasses and digital twin technology. Future research can be oriented towards using this concept for other construction machinery.

Keywords –

Digital Twin, Smart Glasses, Cyber-Physical System, Augmented Reality, Construction Machinery, Tower Crane, Live Monitoring.

1 Introduction

The construction industry continues to expand expeditiously in the modern world. According to the report “Construction global market report 2021: COVID-19 impact and recovery by 2030” by the year 2025, the output volume of the construction will be around $16614.18 billion, with a compound annual growth rate (CAGR) of 7%, with major stakeholders like China, India, and the US leading the growth [1]. The construction industry still faces challenges like stunted technological growth, low productivity, and poor energy utilization as compared to the industrial sectors which are booming at a remarkable rate. [2] Further, due to the nature of the construction industry, accidents always tend to happen on a macroscale. One of the prominent reasons for accidents is construction machinery which is often not operated by well-experienced workers due to a lack of field training, safety awareness, and proper communication. [3]. One of the important machineries is the tower crane which is selected for this research. The tower cranes are however being continuously replaced by unmanned ones in recent years. The number of registered unmanned tower cranes was around 272 in 2015 and increased by 30% to 1826 at the end of the year 2019 according to the report by the Ministry of Land, Infrastructure and Transport, Korea. The increase in the number of such cranes is due to their faster job completion time and lesser costs.

The construction machinery like the tower crane can be controlled using a remote controller i.e., unmanned tower cranes. This requires a connection between the machine and a cyber-physical system which is a computer system mechanism monitored by computer-based algorithms. Abiola [4] has used the cyber-physical system for training workers on safety and postures while Cheng Zhou [5] proposed a cyber-physical monitoring system using the IoT parameters as a safety system for safely monitoring the constructions taking place underground and to increase crane safety. The remote controllers at present can communicate through both wireless and wired connections with the operating machines. The use of AR has also started in recent years and the digital twin is also paving its way in the construction industry. Table 1 provides a brief history of the number of automation approaches used in the past from using the cyber-physical systems connecting the real world to the internet; the use of digital twin copying natural behaviour in a virtual space; a safety system for monitoring and visualizing HMD system. A few papers have been listed along with the main purpose of their research and how they fit in with the construction machinery have been highlighted.

Table 1. Remote Controllers for the Construction Machinery

Author Title	Purpose	CPS	DT	SS	SG
M Y Cheng (2001)	Real-time computer simulation for shotcreting robot	✓	○	○	○
T Sasaki (2008)	Computer simulation for a backhoe	○	○	✓	○
S Moon (2010)	CAD-based path simulation for concrete surface grinder	✓	○	○	○
Y Li (2012)	Alarm monitoring simulation for tower crane	○	○	✓	○
P Lin (2013)	Real-time site state visualization for safety workers	✓	○	✓	○
A Jardón (2014)	Video target guidance for micro tunneling machines	✓	○	○	○
S Ruan (2017)	Sensor monitoring for unmanned tower crane	✓	○	○	○
R Sekizuka (2017)	AR training simulation for hydraulic excavator	○	○	✓	✓
SM Hasan (2021)	AR interaction with construction machinery	✓	✓	○	○
Z Liu (2021)	Real-time safety of prefabricated building	○	✓	✓	○

*CPS= Cyber-Physical System, DT= Digital Twin, SS= Safety System, SG= Smart Glasses

The approaches have mainly focused on either using the cyber-physical system or providing safety to the workers using some mobile or pad remote controller. There is no present technology that combines all the four concepts to give us a network that uses a cyber-physical system to provide safety while incorporating the concepts of digital twin using smart glasses. An approach to use the remote controller while providing a virtual model to assess the capabilities and monitoring of the model can be done by making a digital twin. The concept of the digital twin is to provide an exact twin model to its real counterpart which also copies all the functions. The use of digital twin (DT) has recently started in the construction industry. The DT technology provides the opportunity for the integration of the physical world with the digital world and has attracted much attention. Emergen Research estimates the digital twin market size to reach USD 106.26 billion with a steady CAGR of 54.7% in 2028 [6]. Hou [7] stressed the use of the digital twin in the safety of the workforce of construction using sensor and visualization technology. Alizadehsalehi [8] provided a generic framework to use DT through a monitoring system called DRX.

The framework comprising of the digital twin, the CPS, and the construction machinery need a communication process that does not have long durations, is easy to handle and can be accessed by all stakeholders. Communication in the construction industry still follows the conventional method of using phone calls and in some cases, video calls and emails. However, this does not address many problems as it is difficult to analyse without complete visual perception and spatial interaction. It is also not advisable that high-level staff be present on the construction site for every minor issue. This approach of using the construction machinery monitoring research has rarely been touched in the past. The solution is to have a device and controller that can make communication easier without disrupting the workflow.

AR Smart glasses offer the technology to access both the digital twin and the construction machinery whilst leaving the hands free to focus on the tasks. While these glasses are continuously being used in other forms of industries like medicine, their demand in the construction field is yet to thrive. Wang S. provided a solution to using the smart glasses for the damage detection of the structures using deep learning and augmented reality techniques [9]. De Luca D. integrated the mixed reality platform and BIM with the help of smart glasses in the construction field [10]. Pierdicca R. has given the concept of using the augmented operator using the smart glasses to act as a guide system for the operator during the working process while the author has also given another concept of training on the job site using the AR glasses [11][12]. Although, in the past, the steps for the safety of workers have been provided using smart glasses; no solution exists for integrating the safety, sensor data, and communication elements into a single skeleton for the user. This paper, however, discusses a solution to combine the digital twin and cyber-physical systems for a construction machine using the augmented and mixed reality with the help of smart glasses.

2 Proposed Solution

Numerous solutions have been provided in the past for overcoming the problems of construction automation. Recently, pad controllers(using mobile phones or tablets) are being used to control the construction machinery. However, it is difficult to always carry the pad, does not provide the spatial view and for an unskilled worker is hard to control it. There is also no actual solution existing for controlling a real prototype of a crane model or any other construction machinery using some sort of eyewear of head-mounted device wirelessly. It is possible to experience a less damaging and efficient functionality by using smart glasses which also provide accurate inspection of the structures and the ability to communicate with experienced personnel in real-time. With access to smart eyewear, it is easier to interact with the construction machinery and the digital twin. First, the use of the glasses is tested to see if they provide robust and fast access to the assembly of controlling the machinery. Second, the testing is done through the HMD to know the potential benefits of using it on the construction site. Figure 1 defines the workflow of the proposed method which follows 7 steps combining the cyber-physical system with the digital twin into the smart glasses for operation.

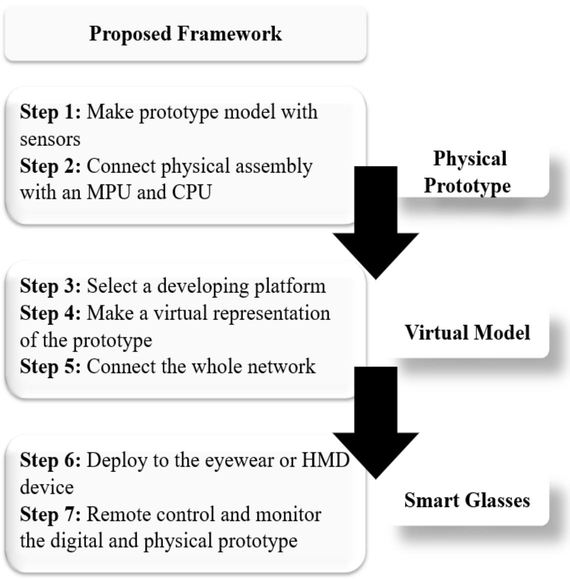

Figure 1: Workflow for the proposed method

3 Development of Remote-Control System

The digital twin framework for combining the virtual space with the physical space requires a prototype to test how the real model will work out in real-time. The development of the system encompasses four steps i.e., the creation of a cyber-physical prototype followed by the selection of a developing platform, making the virtual model, and lastly the incorporation of the smart glasses(eyewear and HMD) to the whole structure.

3.1 Cyber-Physical System

The physical model is the representation of a tower crane with the framework comprising of two servos, one ultrasonic sensor, and the metal assembly. The model is connected further to an Arduino Uno Board using a breadboard which further gets connected to a laptop/PC. Figure 2 explains how the assembly relates to each other to mimic a visualization of the tower crane. Two servos have been used for the physical model. The specifications of the servo are Parallax Standard Servo which can hold any position over a 180-degree range controlling the crane arm and the Parallax Continuous Servo which is designed for continuous rotation and spins whole 360 degrees, so it controls the hook motion.

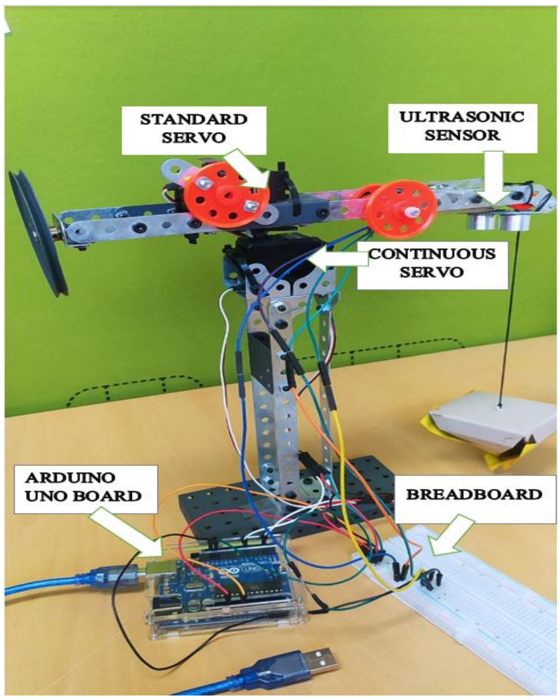

Figure 2: Physical Model for the prototype

The continuous servo is attached with a pulley which is again attached with a secondary pulley with a rubber band helping in the movement of the attached block which serves as our model weight to be lifted. An ultrasonic sensor HC-SR04+ is selected owing to its accurate range, ability to provide continuous distance readings, and performance is not affected by weather conditions. The accuracy provided is up to 3mm and it can detect the distance from 2-400mm. The wires are first attached to the components i.e., standard servo, continuous-servo, and ultrasonic sensor and goes into the breadboard which serves as a connection hub, and then only the relative voltage, ground, and sensor pins are attached with the Arduino Uno board. The microcontrollers are the heart of any robotic device and help to make seamless communication between the user and the related device. Arduino is a prototyping platform that is used for making electronic objects. The platform provides an open-source software known as Arduino IDE, which makes it possible to communicate the microcontrollers such as Arduino Uno with Windows, Linux, or the Mac OS. Arduino IDE version v1.8.13 is used for connecting the physical model with the computer to send the commands between said devices. The board selected is Arduino Uno.

3.2 Developing Platform

A list of the top application and game engines that can help in making the software for the required purpose is presented in table 2.

Table 2. Platforms available for Development

Application Platform	Android	iOS	PC, Mac, and Linux	Universal Windows Platform
Unity	✓	✓	✓	✓
UE4	✓	✓	✓	✓
Godot	✓	✓	✓	○
CryEngine	○	○	✓	○
Gdevelop	✓	✓	✓	○
Corona SDK	✓	✓	✓	○
Construct 3	✓	✓	✓	✓

The best alternatives to use include Unity, Unreal Engine 4, and Construct 3 considering we need to deploy to the HMDs. Construct 3 is not free, between the Unreal Engine and Unity the latter provides better ease of access, developer support, wide assets store, and a vast range of tutorials so Unity is the most suitable option as most of the eyewear have the official support with Unity. Unity is a real-time development program used for creating interactive and real-time content incorporating the concepts of artificial and virtual reality. The engine has found its way into the architecture, engineering, and construction(AEP) industries helping in connecting the BIM data with the major stakeholders of the construction phase. The software provides the user to develop a scene with all the elements required and then deploy it to the necessary hardware device. Unity version 20.2.6f1 is used for this research as it has all the necessary plugins and continuous support from the developers. The noteworthy features include the Vuforia which is used for the development of augmented reality applications and the MRTK toolkit for the development of mixed reality applications. Recently, only two open-source platforms are available for development on the HMD.

3.3 Virtual Model

The digital twin of the model is made using Blender v2.92 as the open-source software gives the ease of access as well as the ability to directly export the file to our simulation software i.e., Unity. The dimensions of the original model are replicated in the digital twin and a conjugate image of the model is made using the creation software blender. The base of the crane is modeled along with the frame, rope, weight, and pulleys. Although the software supports animation for the model, yet the animating part is done on Unity. The model serves as a digital twin i.e., providing identical movements with the corresponding changes in the physical model. Figure 3 gives a demonstrative look at the digital twin. The model is a direct replication of the physical twin to provide more conformity with the original model to see the output clearly as opposed to a conventional tower crane model.

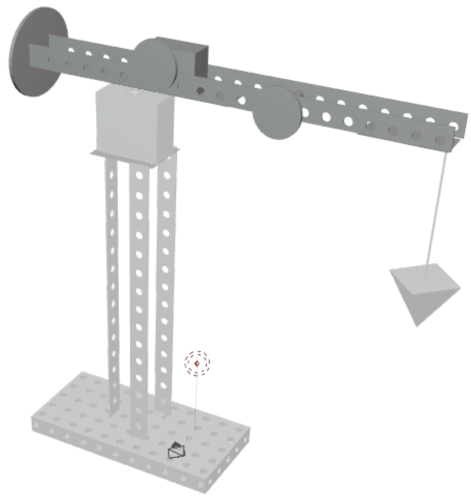

Figure 3: The digital twin model for the prototype

3.4 Smart Glasses Integration

An application is developed, and the two different computer setups are done for the connection of the physical prototype with the virtual model. Consideration of how the eyewear operates and their functionality, the two setups differ in the interface and input methods:

3.4.1 Eyewear

The eyewear glasses provide display in only one eye and the three physical buttons with a touchpad are the only form of inputs available to the glasses. Using the Unity working environment, the interface is created in such a way that provides the relay between the server and client easily. Figure 4 shows the multi-way communication between the main three elements. The server can send commands to both the glasses and the physical model whereby the glasses can also do the same vice-versa. The physical model moves according to both the server and client and gives the value of the sensor i.e., the ultrasonic sensor reading back to both devices.

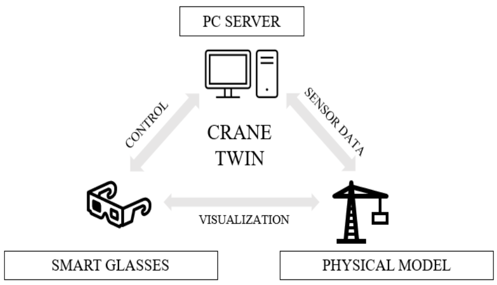

Figure 4: Multi-Way Communication Between Physical Model, Smart Glasses, and PC Server

The interface consists of the distance from the ultrasonic readings as well as the angle for both servos. When the connection is made between the device and server by providing the I.P address and using the correct Wi-Fi, the data can be transferred from the physical model to the server and then from the server to the client i.e., the eyewear. Upon the successful connection, the sensor data gets updated continuously and the button "Camera" can be clicked to open the live interface. Vuforia is integrated into the assembly to provide the marker for the digital twin. The digital twin then gets updated with the respective input commands that are given to it. Figure 5 shows the interface of the application working on the glasses. The interface consists of buttons for controlling the crane arm and the hook as well as the output areas for the sensor readings. The 'Move Up' and 'Move Down' commands control the hook of the model while the 'Move Left' and 'Move Right' Commands control the crane arm. The distance from the sensor is calculated by first getting duration from the ECHOPIN reading when it is set as HIGH, then it is multiplied by the speed of sound and changing the cycle distance to only one side distance. The network IP address must be inputted manually using the physical buttons and the trackpad for seamless communication that helps the user to control the construction site while a construction manager can also check the sensor data while sitting in the office. Since the eyewear just sits on the eye and there is no need to hold it continuously, it provides a comfortable user experience. The control is present between the PC server and smart glasses meaning both can specify commands individually while the visualization occurs on both the crane model and the smart glasses to see what is going on with the prototype. Sensor data is transferred from the prototype to the glasses and the pc server to and forth so that it is possible to make multi-way communication possible.

The values in front of the distance i.e., the ultrasonic value readings are to assess the distance from the ground to the hook. So, when the value reaches an undesired value, the worker operating the eyewear can assess if any unconditional hazard is to occur. Lowering the sensor will lower the distance value shown on the screen and appropriate height can be assessed as to not hit anyone working on the site.
The interface made using the Unity platform provides a simple controller for the machinery with scripts attached to buttons. Clicking buttons send a command to the Arduino which is also programmed to know what to do when the button is pressed and then after processing the data request, it sends the output back to the user.

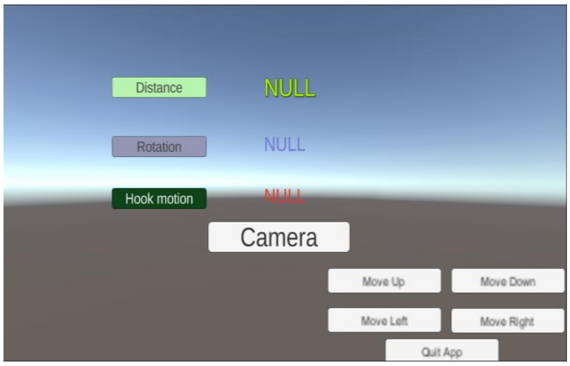

Figure 5: Interface of the application for Eyewear

3.4.2 Head-Mounted Device

The HMD provides a fully immersive experience for the user. The input can be done through eye and hand gestures. The Unity working environment with the help of the Mixed Reality Toolkit is used for making the interface for the assembly. The change here is the use of movement sliders to control the crane arm and the hook of the model. The model is placed using the spatial awareness feature of the HMD through marker-less AR technology.

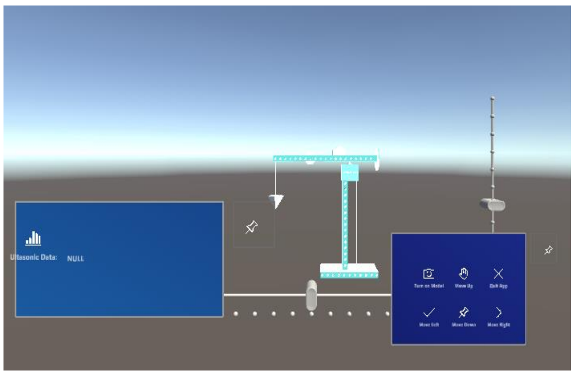

Figure 6: Interface of the application for HMD

The data from the ultrasonic sensor now appears on a hologram and there is a separate user interface for controlling the animations of the model. The networking adopted for this is Photon Networking allowing access between the user and server competently. The hand gestures make it possible to interact with digital twins easily. Using the HMD, the input commands can be sent to the server which then communicates with the physical model whilst also the digital twin appearing as a Mixed Reality object can be controlled using the HMD. The separate hologram showing the distance can be moved and adjusted anywhere using the HMD technology called the "Near Object Interaction" and the "Box Collider". Availability to resize the digital twin is also available with the use of the 'Bound Control' option. Like the eyewear, the sensor data is relayed from the physical model to the server first, and then with the help of proper networking, it is transferred to the HMD. From Arduino, functions like servo are used to send commands to the Arduino for movement, and Serial is used for getting the read and write data for the sensor. The data is converted into a string and then it is displayed. Using the serial command, the data is first fed from the Arduino to the Unity where it is then visualized properly. The scripts are attached to each button for moving the digital twin model and displaying the results.

A sample script for the servo is shown in figure 7. Two servos are used as described earlier so the movement sliders are set in such a way that when the horizontal slider is moved the servo pin automatically changes to the corresponding up/down motion pin and the prototype moves. Similar is the case with the hook motion, where controlling the slider on either the screen or in the head-mounted device makes it possible to send a number to change the pin to the Arduino, and then it sends to the prototype.

```
using System.Collections;
using System.Collections.Generic;
using UnityEngine;
using UnityEngine.UI;
using TMPro;

public class setValue : MonoBehaviour
{
    public TextMesh ServoPin;
    // Start is called before the first frame update
    void Start()
    {
        ServoPin = (TextMesh)GameObject.Find("servoPin").GetComponent<TextMesh>();
    }

    // Update is called once per frame
    void Update()
    {

    }
    public void setToX()
    {

        ServoPin.text = 2.ToString();
        //servoPin = 2;
    }
    public void setToY()
    {
        //  Menu.pinMode(7, PinMode.Servo);
        ServoPin.text = 7.ToString();
     //   servoPin = 7;
    }
}
```

Figure 7: Sample script for controlling movement

4 Results

The application for the smart glasses consists of the sensor distance reading, the rotation angle, and the movement of the hook up and down. It is possible to use the three physical buttons available on the glasses to send commands to operate both the 3D model as well as the prototype of the tower crane. There is also the option to use the trackpad to control the cursor and click on the "Move Left" and other commands. The exact ultrasonic readings in cm and servo's angle in degrees appearing on the server appear on the client i.e., Eyewear, and the multi-way communication between three devices is working.

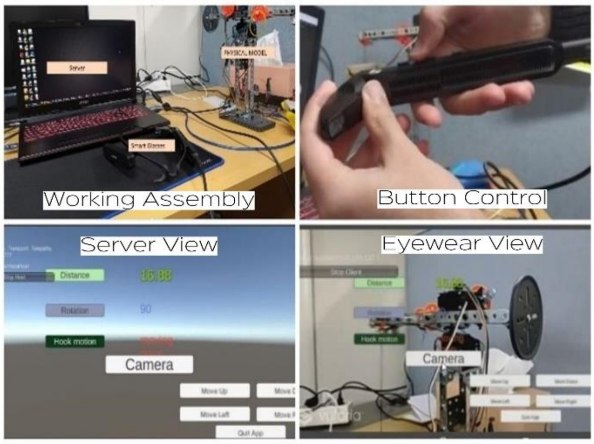

Figure 8: Working process for Eyewear

Figure 8 shows the working process of the eyewear where first has the assembly set up where the prototype is connected to a laptop which also acts as a server. Using the Wifi connection, the eyewear is connected to the laptop also. The application is then started on both the server(laptop) and the eyewear(client). The button control tells that when the application starts, we either have the trackpad to control the movement and interface or we can also use the side buttons for this purpose. Server view illustrates the actual graphical user interface present when the application is turned on in the laptop or server while the eyewear view shows what the user visualizes when he wears the hardware. The distance is shown in figure 8 which tells the measurement from the weight object on the hook of the machinery to the ultrasonic sensor. The rotation angle specifies the angle from the original position while the hook motion shows whether the hook is moving up or down. A network connection is made possible for the eyewear using a Unity plugin 'Mirror Networking'. The distance reading showing the figure is the ultrasonic sensor and the rotation angle as well as if the hook is moving up or down is also being monitored continuously through both the server and multiple clients. The animations for the digital twin are made in synchronization with the actual model to mimic the real behavior and the control buttons especially the hardware keys are assigned the controls for moving both the digital twin and the cyber-physical model at the same time. The communication takes place as soon as there is a connection on all the devices and there is smooth communication between the transferring of data between the devices.

Figure 9: Working Process for HMD

The working assembly is like the eyewear except that the eyewear is now replaced with the head-mounted device. Here gesture control means that with the use of gestures, it can control the movement and work. The server view shows what happens on the server during the simulation while the HMD view shows what the user can see, and which objects can he interact with. Likewise, results for the HMD are obtained and illustrated in figure 9 which shows the hologram displaying the value of ultrasonic sensor data reading and it is continuously being updated as the crane model changes in real-time. The HMD has a different operating system and the application working for the solution is distinct from its counterpart. The readings from the ultrasonic sensor in cm appear in a hologram now, there is the option to control the digital twin only, and sliders can help in the movement of the crane vertically and horizontally. The holograms and the model can also be pinned and move anywhere owing to the spatial interaction provided by the HMD.

Table 3. Comparison with existing hardware

Functionality	Existing	Eyewear	HMD
Input	Touchscreen	Trackpad	Gestures
Live touch	○	○	✓
Portability	○	✓	✓
Multiple users	8	64	64

Table 3 provides a comparison of the existing devices with the eyewear and HMD. The HMD provides the most functionality to use while supporting features like spatial interaction where a person can interact with the environment and 3D objects intuitively.
The results show that it can coordinate the multi-way communication between the devices and simultaneous data transfer and monitoring can be done with a wireless connection. The need for controlling construction machinery with the help of smart glasses i.e., the eyewear and the head-mounted device, is achieved, and the digital twin functions well with the cyber-physical system to provide the required framework of a true wireless communication helping to monitor, control, and visualize making communication process adequate. Table 1 highlighted some of the approaches used in the past for remote control operations. The construction industry is using smart glasses for environment monitoring [13] and object recognition [14].
BIM data is also being monitored using the safety smart glasses to visualize the actual site condition as well as to compare the BIM model remotely [15]. Finally, a framework is proposed to combine the digital twin (DT) and cyber-physical systems (CPS) into smart glasses (SG) for operating construction machinery. Based on the physical prototype model of a tower crane with sensors, its virtual model was made, and smart glasses were deployed to remote control and monitor the digital and physical prototype. Portable smart glasses showed sensor distance, rotation angle, and movement information, implying that monitoring in the construction sites can be done with a wireless connection. By allowing both servers and glasses to control and monitor, the system facilitates collaboration and supervision on construction sites.

5 Conclusions and Future Work

The construction site always suffers from accidents and safety considerations need to be monitored continuously to avoid damage. The purpose of this research is to provide an integrated framework where it can wirelessly control the construction machinery using some eyewear and head-mounted devices. There is no more need to continuously hold the remote controller when it can be always worn providing better feedback and safety aspects. One thing to note while designing the interface and the algorithm is to worry about the safety aspect like how to ensure that collision does not occur with the nearby objects and workers. The work for safety is still under development and right now the focus is monitoring and controlling the models together. The idea is by using the spatial awareness system on the HMDs, it is possible to devise the collision system for the construction machinery so that nearby workers and objects are protected. On the construction site, the idea can be implemented where the safety worker wears it on the site whilst the major stakeholders can monitor the activities from the office. The tablet is good for indoor use considering its size, the Eyewear is growing as an accomplished device in the construction field and can be used for both indoors and outdoors while the HMD is easier to use and provides the best performance in a spacious environment. The HMD also provides the option for Iris detection for security purposes, and it can be incorporated in the interface to allow for a more real-life situation of only letting the experienced staff whose iris is stored in the database be able to access the application. This is under consideration for future work. Moreover, construction machinery like excavators, bulldozers, and loaders can be consolidated with this idea to make a more intuitive yet powerful application to control all sorts of devices used in the construction site. The basic functionality to control the cyber-physical model using the smart devices are successfully tested and if more focus is given to the concept, a lot of different functionalities can be explored. Further, the cross-platform option is also under consideration where devices operating on the different O.S could also interact.

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