Intelligent Mixed Reality Platform for CNC Machine and 3D Printer Operation and Management

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Abstract. The advancement of mixed reality (MR) technology presents significant potential for transforming advanced human-machine interactions in the manufacturing regime. By seamlessly mixing digital and physical elements, MR creates immersive and interactive experiences for users during the machining operation. On the other hand, current manufacturing machine operations, such as CNC machines and 3D printers, still rely heavily on physical controllers, with each brand of machine featuring distinct control panels that require extensive training. Moreover, fixed control panels significantly constrain their ability to accommodate rapidly evolving functionalities, such as digital twins, machine learning, and AI integration. As CNC machining and 3D printing are among the most versatile and widely utilized manufacturing methods, this paper introduces an MR platform designed to control these processes with a single MR application. The platform provides a customizable, step-by-step guided user interface on the Microsoft® HoloLens 2, designed to simplify the learning process and reduce the learning curve. The platform's architecture is highly extensible, allowing the integration of different types of machines and sensors for real-time process monitoring. Furthermore, a unified server facilitates the incorporation of advanced machine learning and artificial intelligence techniques in the future, paving the way for smarter, more efficient manufacturing processes.

Keywords: Mixed Reality, CNC control, 3D printing, human-machine interaction.

1 Introduction

Virtual Reality (VR) and Mixed Reality (MR) are emerging immersive holographic technologies that blend digital and physical environments, enabling new ways of interaction and visualization. They have greatly enhanced the current manufacturing industry, becoming a key technology in Industry 4.0 [1], [2]. Compared with VR, the see-through capability of MR enables it to play a vital role in visualizing manufacturing information in a flexible and interactive manner. 3D geometry models, animations, and real-time data can innovatively be visualized through these devices to further improve working flow, optimize decision-making, ensure operation safety, and strengthen training efficiency [3].

Due to the immersive nature of VR and MR, many researchers explore a more intuitive human-machine interaction mode using various VR or MR hardware than a traditional desktop or tablet-based interface. Incorporating digital twins (DT) with VR or MR allows the user to monitor the real-time machine status while interactively controlling the machine [4]. For instance, Zhu et al. [5] developed a framework for CNC machining on AR applications to visualize the data during the manufacturing environment, enabling comprehensive information acquisition, efficient decision-making, and high-level machine control. However, due to the limited openness of CNC systems, the developed framework faces challenges in providing real-time direct control to the CNC machine. Guler et al. [6] developed an AR-based machining simulation system that can help operators check the toolpaths directly on a real machine. The novel interaction not only eliminates the need for full machine modeling and complex theoretical modeling but also enables accurate, collision-free setups for users.

Fused filament fabrication (FFF) is one of the most widely used additive manufacturing methods for prototyping and rapid manufacturing. Mourtzis et al. [7] present an FFF DT architecture designed to monitor and optimize the printing process. This framework offers insights from historical data to recommend printing parameters, thereby enhancing printing quality. Similarly, Paripooranan et al. [8] proposed a DT for a commercial desktop FFF 3D printer on an AR device that visualizes printing parameters and provides real-time error alerts to users. Meanwhile, the platform enables some basic control functions for the 3D printer using the AR device, thereby achieving a two-way exchange of information. Despite these advancements, the current AR and MR applications are still built around the conventional functions of machines, restricting the customizability for next-generation HMI. As operations become more complex, users will spend more time learning the interface and interpreting contextual instructions in the VR or MR environment. Moreover, current research primarily focuses on VR/MR interaction with a single machine, lacking scalability and adaptability to different machines within the same platform. With the increasing demand for one operator to manage multiple machines in parallel within a machine shop, developing a unified platform for multi-machine control has become increasingly urgent.

VR or MR environment for machining training has also showcased distinct advantages in reducing potential hazards and enhancing the efficiency of the learning process [9], [10], [11]. The VR/MR-based training system is also able to minimize the gap between experienced operators and new operators. A growing number of researchers have been actively working on developing and implementing VR or MR applications for training machine tool operators [11]. Ryan et al. [12] proposed a VR training system with error management for CNC machining training. In the system, trainees are able to actively explore the spatial teaching environment while operating a virtual CNC machine with auditory and text instructions. Compared to the VR environment, Yang et al. [3] developed an AR training system that allows the trainee to directly interact with virtualized machines in a real environment with natural operation behaviors, demonstrating lower failure rates and inquiry times than video training. Although VR or MR-based training systems can effectively increase learning efficiency and reduce cost, most reported training systems rely on text or auditory instructions for training. The trainee still needs to remember the details of operation procedures correctly. The virtual learning environment cannot inherently simplify the operation procedure, thereby reducing the cognitive load and lowering the learning difficulty.

In this paper, we aim to present an adaptable MR platform for the control and management of multiple machines in parallel. The user is able to operate and manage multiple types of machines by wearing a single Microsoft HoloLens 2 headset. To minimize training requirements and human errors, we introduce a customized step-by-step holographic UI, allowing users to operate the machines intuitively without memorizing complex physical panels and procedures. Leveraging IoT technology, real-time machining data and human data can be collected to a unified server and displayed on the HoloLens for monitoring. In this paper, the system architecture is introduced, and detailed implementation methodology is provided in the following sections.

2 System Architecture

The platform employs a unified server built on the .NET framework to coordinate communication between client devices, machines, and an MQTT broker [13]. As shown in Fig. 1, the server is designed to be independent of both hardware and user interfaces, allowing multiple devices to be controlled in parallel without requiring clients or machines to maintain knowledge of the entire network topology. Stable and reliable communications (e.g., real-time control) are achieved through session-based WebSocket [14] connections for continuous interaction between the client and server, while on-demand WebSocket connections handle command execution between the server and machine controllers. Additionally, MQTT-based telemetry streaming ensures efficient massive data exchange and real-time monitoring. This hybrid architecture consolidates high-volume data flows and optimizes operation performance. Moreover, the unified server creates a foundation for future implementation of intelligent algorithms, such as machine learning, predictive analytics, and automated fault detection.

Another key architectural innovation is the plug-in-based system that enables high scalability and adaptability to different machine types, such as 3D printers and CNC machines, without changing the core infrastructure. Each machine interacts through a customized plugin, abstracting device-specific logic (e.g., G-code processing for CNCs and 3D printers) into a standardized framework. This plugin approach ensures cross-compatibility across different machines while maintaining a unified control interface.

As shown in Fig. 1, the following workflow outlines how the system facilitates machine discovery, command execution, and real-time telemetry processing:

1. The HoloLens 2 Unity application establishes a persistent WebSocket connection with the unified server upon login through a QR code scanning. The server verifies the client, initializes session resources, and loads the appropriate interface plugin for machine control.

2. The unified server dynamically subscribes to only active machine topics via

MQTT using the machine plugin, preventing unnecessary data flow. Machines continuously publish telemetry updates, which the server processes based on both the machine's current state and the user's workflow phase.

3. When the user initiates an operation, the HoloLens application sends the command via WebSocket to the unified server. The server then establishes an on-demand WebSocket tunnel with the respective Raspberry Pi controller, forwarding the command in the machine's native format for execution.

4. Upon task completion, the server closes the temporary WebSocket connection, freeing system resources.

5. As machines continuously publish real-time status updates via MQTT, if an anomaly is detected, the server pauses operations and sends an alert to the operator through the HoloLens UI, ensuring immediate intervention.

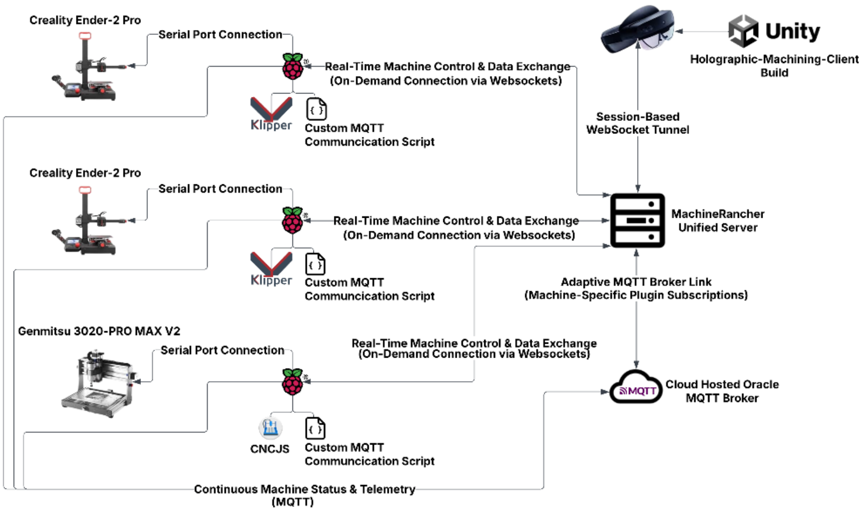

Fig. 1. The illustration of system architecture.

3 Implementation

In this paper, we evaluate the scalability and adaptability of our architecture by implementing it on a CNC desktop machine and two FDM 3D printers, which are two widely used manufacturing methods. To enhance usability for beginners, we customized the MR user interface (UI) to align with a standard operational workflow. In this project, we used a Microsoft HoloLens 2 headset to run a client developed in the Unity® game engine with the Mixed Reality Toolkit (MRTK) library. This library also supports most other major VR/MR devices, allowing it to be easily ported to more devices in the future. By leveraging the MRTK QR code scanning API of the HoloLens 2, the MR system assigns a unique spatial anchor to each CNC machine, enabling parallel usage of machines while also remaining unique to each machine instance. Our platform aims to allow users to operate all deployed machines in the machine shop by simply wearing an MR headset and looking at a QR code above the machine to initiate operations.

3.1 3D printer Implementation

In order to make the platform scalable and adaptable to various 3D printers, the platform leverages Klipper firmware [15] running on a Raspberry Pi 5. Klipper enhances printer performance by offloading complex computations to a more powerful general-purpose computer, such as Raspberry Pi. In addition, it is integrated with Moonraker, a Python-based web server that exposes APIs, allowing client applications to interact with the 3D printing firmware [16]. The platform establishes on-demand WebSocket connections to send printer control commands to Klipper using JSON-RPC, a lightweight remote procedure call protocol. Furthermore, the Raspberry Pi hosts a custom Python 3 script that subscribes to Moonraker's API end-points and continuously publishes printer status, sensor readings, and error messages to the cloud-hosted MQTT broker. This ensures low-latency monitoring for the client-side application. By handling printer management at the server level, this architecture allows the unified server to dynamically oversee active printers without requiring direct client interaction, significantly improving system efficiency.

Building on our previous research [17], a step-by-step MR interface was developed for 3D printer operation and management, as shown in Fig. 2. Traditional HMIs require operators to navigate complex menus and manually track procedural steps, increasing the likelihood of errors, missing steps, and safety risks. To address these challenges, the MR-driven workflow provides real-time, step-by-step guidance to alleviate the learning curve and challenges that naturally come with traditional HMI. The platform also supports parallel management of multiple printers using spatial anchors. By scanning a QR code attached to each printer, the HoloLens 2 assigns a printer's physical location within the MR space, allowing users to access machine-specific data simply by approaching the device.

Fig. 2 illustrates the structured five-step workflow of MR-based 3D printer control, developed to optimize printer management and enhance print accuracy.

1. The user scans the QR code attached to the 3D printer using the embedded camera in HoloLens 2, establishing an anchor point in MR space. The system notifies the server, which loads the appropriate machine plugin and subscribes to the printer's MQTT topics.
2. The user initiates auto bed leveling at the beginning, prompting the client to request the server to start the process. The server establishes a WebSocket connection and retrieves bed probe data. The HoloLens UI then displays a holographic model of the printer's bed, guiding the user to adjust the bed level through screw adjustments.
3. After bed leveling, the server fetches the last known printer information from MQTT and displays it for user updates and confirmation. The user can accept or modify settings based on their selected G-code file and printing materials.
4. The user selects a G-code file and views an interactive holographic model of the print to check the details. A pre-print simulation was developed to help diagnose potential failures. The simulation includes a parsing algorithm to

correctly interpret the G-code file.

5. When the user initiates the simulation, the simulation starts a coroutine, which either seeks to gradually simulate the print to mimic the printer's actual behavior, or it can rapidly simulate to show the completed print job.
6. Before printing, the server also retrieves G-code metadata (added in the G-code header), compares it with the digital twin, and alerts the user to any configuration mismatches in Step 2.
7. The print job begins, and the user monitors a live view displaying bed and extruder temperatures (or any other useful data). The system also ensures session persistence, returning the user to the correct UI if they restart the application during an active print job.

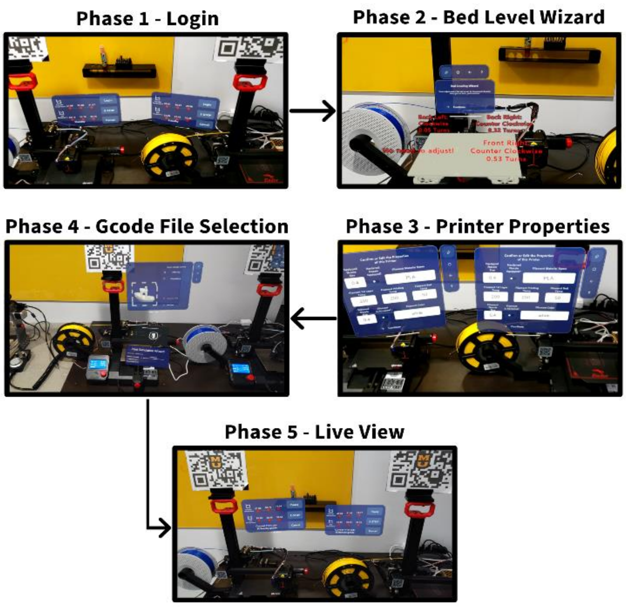

Fig. 2. Illustration of 3D Printer Workflow.

3.2 CNC Implementation

To enhance the versatility and user accessibility of the platform, we customized CNCjs [18], a web-based interface compatible with CNC controllers Grbl. Grbl [19] is an open-source firmware that enables precise control of most CNC routers and machines. Running on Raspberry Pi 5, CNCjs facilitates remote CNC management through Socket.io connections, allowing real-time machine control and monitoring. To streamline user interaction, we've developed a lightweight C# .NET application that interfaces with CNCjs. This custom script subscribes to CNCjs's events, capturing continuous data such as machine status, sensor readings, and error messages, and publishes this information to designated MQTT topics. This mirrors the data flow established for our 3D printers, ensuring a consistent user experience across different machine types.

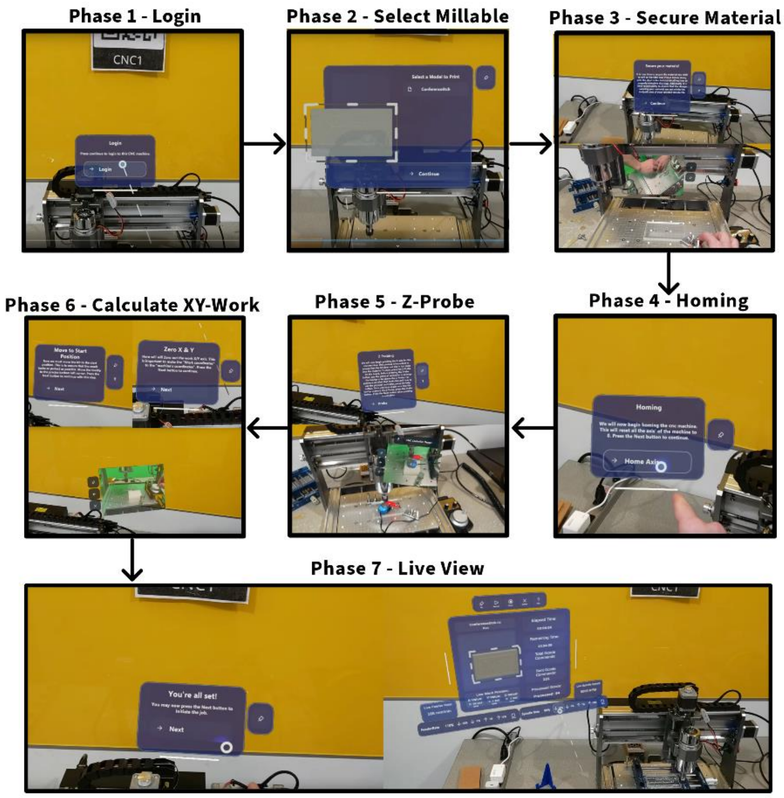

Fig. 3. Illustration of CNC Machine Workflow.

Fig. 3 showcases the CNC workflow designed to minimize setup time, enforce operation correctness, and improve real-time monitoring. The HoloLens UI facilitates step-by-step guidance for machine login, workpiece securing, homing, work offset setup, tool length setting, and G-Code execution. In order to reduce the cognitive load and lower the learning difficulty, a tutorial video is embedded to guide the work offset setting and Z-probe setting, which are two crucial steps for the success of CNC machining. Additionally, the UI provides an intuitive live view for monitoring the milling process, adjusting feed rate and spindle speed, and ensuring seamless user control over industry-standard CNC operations.

The following steps outline the user-machine interaction, live data management, and CNC manipulation:

1. The user logs in by scanning the QR code using HoloLens 2, which sends an authentication request to CNCjs. The server validates the user via a Bearer token, establishes a connection with the Socket.io server, and links to the CNC machine's serial port.
2. The UI presents a list of available G-Code files. Upon selection, a holographic visualization of the job is displayed for confirmation. The server then loads the G-Code file into the Grbl controller.

3. The user follows a tutorial on properly securing the material to the CNC bed, ensuring clamps do not interfere with the toolpath.
4. The user clicks “Home”, prompting the server to send a homing request. Once completed, the server finalizes the handshake, allowing the user to proceed.
5. The UI provides a step-by-step video guide on setting up the tool length offset and using the Z-probe to ensure accurate height calibration.
6. The user is guided through positioning the tool tip at the correct starting point before confirming the XY work offset.
7. The live view interface displays real-time work positions, elapsed/remaining time, and processed G-Code commands. Users can pause, resume, adjust feed rate/spindle speed, and trigger an emergency stop (E-stop) as needed.

In this paper, we validate the developed platform by enabling a user wearing the HoloLens to control a 3D printer for printing a stand and operate a CNC machine to engrave an acrylic board, as shown in Fig. 4. The case study demonstrates the ability to control and manage multiple types of machines in parallel, highlighting its potential for smart manufacturing. Additionally, despite having limited machining experience, the user successfully completed the project using our system, demonstrating its ability to enhance training efficiency and its potential for manufacturing training.

Fig. 4. Photo of a manufactured part using the developed MR system.

4 Conclusions and Future Work

This paper presents an intelligent MR platform designed to enhance the operation and management of CNC machines and 3D printers. By integrating MR with a step-by-step guided user interface on the Microsoft HoloLens 2, the platform aims to simplify machine operations while improving workflow efficiency and safety. The implementation of this platform on CNC machines and FFF 3D printers demonstrates its scalability and adaptability across different manufacturing processes. The MR-based interface not only provides an intuitive and immersive user experience but also supports enhanced visualization and real-time feedback through digital twin integration. The platform reduces the complexity of machine operations, lowers error rates, and enables operators to manage multiple machines in parallel.

Future work will focus on expanding the platform's capabilities by integrating additional advanced technologies. Although a large amount of data has been collected on the unified server, it has not yet been fully utilized for smart manufacturing. In the future, AI-driven optimization will be deployed on the unified server to further improve usability and efficiency. Additionally, user studies will be conducted to evaluate the effectiveness of MR-based training and operational interfaces in comparison to traditional methods. Although not detailed in the previous sections, we successfully collected eye-tracking data on the unified server using the embedded sensor in HoloLens 2 for human data analysis during machining. By bridging the gap between human-machine interaction and smart manufacturing, this MR platform represents a significant step toward the future of intelligent, flexible, and user-friendly manufacturing environments.

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