Design and Implementation of a Mixed Reality Human-Machine Interface for 3D Printer Real-Time Monitoring and Management

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Abstract

The rapid advancement of 3D printing technology has catalyzed the emergence of diverse 3D printers for both industry and consumer applications. Various brands of 3D printers feature different operation interfaces. Although they have similar operation logic, users often face a steep learning curve when operating them in the beginning. In this paper, we leverage the advantages of Mixed Reality to redesign the human-machine interface for 3D printers. Compared to traditional module-oriented interfaces, we introduce a task-oriented interface to simplify 3D printer operation and minimize potential human errors. We also integrate various sensors to enable real-time monitoring of printer statuses while the operator is in MR. The new platform also allows the operators to supervise multiple pieces of equipment simultaneously. More importantly, this methodology can be readily expanded to other manufacturing machines to revolutionize human-machine interaction in the industrial domain.

Keywords: AR, MR, 3D printing, Human-Machine Interface, IIoT.

Index Terms: Human-centered computing [Human computer interaction (HCI)]: Interaction paradigms—Mixed/augmented reality; Applied computing: Operations research—Computer-aided manufacturing.

1 Introduction

Fused deposition modeling (FDM) 3D printers have become more and more affordable to people and are no longer just for industry applications. Although 3D printers have become more accessible, operating a 3D printer still requires many steps and basic knowledge of 3D printing theory. Additionally, various brands of 3D printers feature different graphic user interfaces (GUIs). New users may face a steep learning curve when operating them in the beginning. Beginners in 3D printing face numerous issues with regard to the complexity of both hardware and software of 3D printing. Therefore, it is urgent to have a human-centered interface to support the rapid development of 3D printing technology.

With the advancement of Mixed Reality (MR), there is great potential to create more human-centered human-machine interaction modes in the manufacturing space. Unlike Virtual Reality (VR), Augmented Reality (AR) or MR does not cover the physical world but mixes 3D virtual objects into physical spaces to provide people with real-time information and interaction with the equipment they are working on [1], such as machining status, maintenance procedures, schematics, and troubleshooting guides. Although some research has successfully used VR, AR, or MR for manufacturing improvement, they mainly provided the user with simple information and instructions, lacking deep interaction between the interface and the machines.

In this paper, we present a novel MR-based platform to change the current method of human-3D printer interaction. Compared to the traditional interaction mode, we present a new customizable task-based MR interface in which the user is guided to follow a safe and standard procedure to operate the 3D printer without a specific training process. The method can be readily scaled up and applied to other machining processes for human-centered manufacturing.

2 Methods

Instead of requiring users to decipher contextual instructions within the MR environment, the novel MR-based interface will provide a step-by-step interactive interface based on specific task requirements, dramatically reducing the cognitive load of learning the interfaces and operations. The design and implementation of our new platform involves two key components: back-end architecture and front-end clients, as shown in Figure 1.

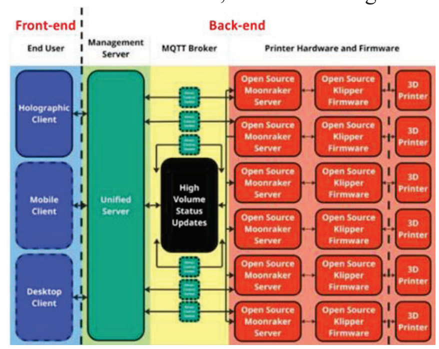

Figure 1: Diagram of the architecture of the MR platform.

The back-end architecture allows for remote control and management of multiple printers via state and behavioral control of each printer. Key elements within the back-end architecture include customized printer hardware and firmware, an MQTT Broker, and a unified server. The back-end architecture enables a highly scalable and robust data exchange capability between printers and front-end clients, providing opportunities for novel automation.

In order to make the platform scalable and adaptable to various 3D printers, Klipper firmware with the Moonraker application is used. Klipper is an open-source firmware for 3D printers that can run on a single-board computer, such as a Raspberry Pi. Moonraker is a third-party application that exposes Klipper functionality via a JSON-RPC API and allows other applications to easily add their functionalities to Klipper. In this paper, we developed several

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custom extensions for Moonraker in order to augment the printer with crucial functionalities, including automatically updating the statuses of printers from sensors or clients and publishing them to the MQTT broker.

To efficiently monitor and control multiple 3D printers, two communication protocols were selected based on the nature of the data transfer required: the MQTT protocol and the WebSocket protocol. MQTT is a lightweight messaging protocol based on the publish-subscribe model, which is suitable for Industrial Internet of Things (IIOT) applications with small computing capabilities and inconsistent network connections. We employed the MQTT protocol for frequent yet simple data transfers (i.e., sensor readings, printer status, etc.) so that clients only need to connect to the MQTT broker to receive the notifications from printers rather than directly linking to all printers. We also adopted the ubiquitous WebSocket protocol for more complex but less frequent data transfers (i.e., remote procedure calls, print requests, etc.). It will enable clients to interact with individual printers at the command line level and receive instantaneous responses from the printer during different processes. Moreover, an optimization was made to run the back-end on a separate server, which can avoid the overhead of needing to discover, connect to, and control printers on the HoloLens.

The front end supports multiple platform clients operated by the user, such as holographic, mobile, and desktop clients. We designed our architecture to facilitate interaction with FDM 3D printers across various platforms, minimizing the need for significant changes to the implementation. For the holographic client, we used the Microsoft® HoloLens 2 with the Mixed Reality Toolkit add-on (MRTK) to simplify development for the HoloLens in Unity, which offers a high degree of customization based on the specific task procedure, visualization requirements, and interaction needs.

Conventional human-machine interface (HMI) design focuses on the functionalities of machines, requiring the user to navigate among menus to accomplish specific tasks. The user must remember each step associated with the machine's functionality in sequence. Any incorrect or missed steps may result in a failure or hazard in the machining process. To solve this problem, we introduce a task-oriented HMI on a holographic client to guide the user in completing the task of 3D printing intuitively. In this paper, we designed the standard operation workflow by integrating the experiences of 3D printing experts, and then customized it to take advantage of the unique capabilities of an MR interface.

Figure 2 shows a user operating an FDM 3D printer using our MR platform with a task-oriented interface. A custom interface appears to help the user manage the configuration of the machine, while the parameters set are verified by the server application. Once verified, the position of the device is combined with information from machine sensors to create a digital twin of the bed, instructing the user to adjust the bed level. Following this, the server verifies printable files based on the current machine's configuration. 3D virtual models can be displayed, manipulated, and examined by the user before printing. Once printing begins, the server constantly monitors the printer for abnormalities and will alert the client in case of any possible failures. Additionally, we take advantage of the spatial "anchors" for each machine to allow the user to see a visualization of printing statistics easily just by walking up to the machine. In the event of a failure, logging information is processed to create a convenient visualization displayed above the printer for failure tracking.

Figure 2: Operation example using developed MR platform.

3 Case Study and Discussion

To evaluate the effectiveness of our platform, we performed a case study to compare users' experiences through a classical desktop interface [2] and our new MR interface. We evaluate perceived task difficulty and user confidence using NASA's Task Load Index (TLX) assessment while measuring time efficiency. The TLX results show that all users rated the new interface as less difficult and more efficient to operate than the classical interface, which is also reflected by the shorter durations. On average, subjects' TLX scores improved by roughly 64%, and their operation time was reduced by around 49%.

4 Conclusions

This paper presents the design, implementation, and usage of an MR-based HMI for 3D printers. Compared to the conventional functionality-oriented interface, we developed a task-based interface using MR to guide users through printer operation intuitively and efficiently. The platform's architecture enables interface customization based on various operation procedures for various machining operations. In addition, the flexibility of the platform allows users to integrate multiple sensors, achieving in-situ and real-time monitoring through intuitive data visualization on MR devices. Case studies show that our platform can greatly simplify the 3D printing operation compared to the classical interface. In the future, more telemetry data will be integrated with machine learning or artificial intelligence algorithms to achieve smart monitoring for more machine types.

References

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[2] https://docs.mainsail.xyz/