The Virtual Factory: Hologram-Enabled Control and Monitoring of Industrial IoT Devices

***Abstract*—Augmented reality has been exploited in manifold fields but is yet to be used at its full potential. With the massive diffusion of smart devices, opportunities to build immersive human-computer interfaces are continually expanding. In this study, we conceptualize a virtual factory: an interactive, dynamic, holographic abstraction of the physical machines deployed in a factory. Through our prototype implementation, we conducted a user-study driven evaluation of holographic interfaces compared to traditional interfaces, highlighting its pros and cons. Our study shows that the majority of the participants found holographic manipulation more attractive and natural to interact with. However, current performance characteristics of head-mounted displays must be improved to be applied in production.**

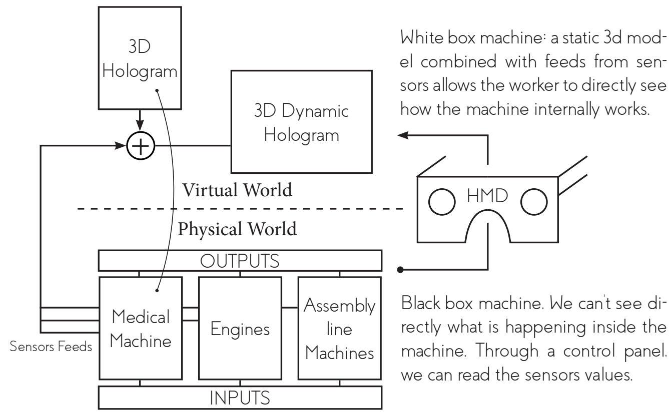

Fig. 1. Bridging Physical and Virtual World

I. Introduction

The integration of smart devices in domestic, industrial and commercial environments has profoundly reshaped the way we interact with our surrounding. Specifically within industry, Internet of Things (IoT) is currently adopted to solve multiple problems as smart labeling [1], energy management [2], control and monitoring [3], demonstrating the constructive uses of digitalization and smart automation.

As machines and industrial physical processes change, the interfaces to interact with them should also change. Until a few years ago, fixing or tuning machines in a factory required manual intervention. Today, most information about the state of physical processes is collected using Supervisory control and data acquisition (SCADA) systems and monitored by human operators. To strengthen the relation between the physical and virtual worlds, we promote the exploration of new interactive experiences via AR. Our primary concern is to understand and evaluate the extent to which AR can help to interact with complex machines through direct, visual, three-dimensional (3D) feedback (although this could easily be extended to other environments).

The wide-spread diffusion of portable head-mounted displays (HMD), such as HoloLens, Lenovo Explorer Headset, HTC Vive, and Oculus Rift, has opened doors to a new paradigm in which the physical world becomes the user interface. AR and virtual reality (VR) have been already utilized in diverse fields, such as tourism, navigation, education, information management. In each of these instantiations, the augmented interface is meant to provide auxiliary information about the surrounding environment to users, thereby helping them to complete specific tasks significantly faster and more accurately [4]. Narrowing our focus to a fabrication scenario, we aim to provide factory workers a more contextualized and visual representation of the real-time, evolving state of a complex machine in the virtual world (through holograms).

Fig.1 shows that with AR, the physical model is represented by inputs, outputs, and readings from sensors. The physical model becomes a virtual, dynamic model based on these parameters. Hence, a potential worker can actually *see* the way a machine works, given the availability of a 1:1 holographic model matching it. Such an interaction has another benefit: it simplifies the knowledge transfer from old to new employees. Half of the human brain is directly or indirectly devoted to processing visual information [5] [6] and presentations using visual aids were found to be 43% more persuasive than unaided presentations [7]. Hence, visual support can help new employees to quickly grasp the ways to work with a complex machine.

Both HMDs and latest smartphones can provide AR experiences. Herein, we focus on the importance of HMD as they offer hands-free interaction, which is a clear benefit when working in a factory (or any other work environment). However, AR glasses (or HMDs) are not supported by a majority of currently available AR solutions. Instead, most AR solution frameworks are aimed at hand-held devices or particular operating systems, such as Android or iOS [8]. Therefore, there is a need to bridge the gap and develop new AR applications especially for industrial environment where the use of hand-held devices is often not possible.

This study presents a prototype framework to enable users to interact with complex machinery and complete tasks via hologram-based interaction. By supplying a dynamic, 3D hologram that changes according to the interaction with nearby smart devices, we want to assess the benefit of providing visual *dynamic* representation on top of virtual information about the system (as in AR annotations [9]). The system comprises three main elements: smart sensors and actuators, the HoloLens HMD, and the Unity engine. In particular, our contributions are as follows:

- Design and implementation of a flexible AR platform where new IoT devices can be easily plugged-in and integrated into the virtual factory workflow.
- A user study to determine the effectiveness of AR-based interaction versus classic SCADA-like systems.
- Insight from the performance evaluation that reveals the limitations of existing HMD devices that deserve future research from the community.

II. System Design and Implementation

Fig.2 presents the three-layer architecture of the system. The IoT layer comprises the network of IoT devices, such as smart sensors and actuators, used to interact with the system. The end-user layer is the core of our system; it provides the holographic abstraction of the physical world. The edge layer is primarily responsible for storage, administration, and organization of the local network; main management operations are handled by this layer. For the initial prototype design, we modelled a complex machinery as an ensemble of embedded boards equipped with sensors and actuators. This design choice forces the users to change their position to interact with different physical controllers; thus, this design choice was particularly important in our user study.

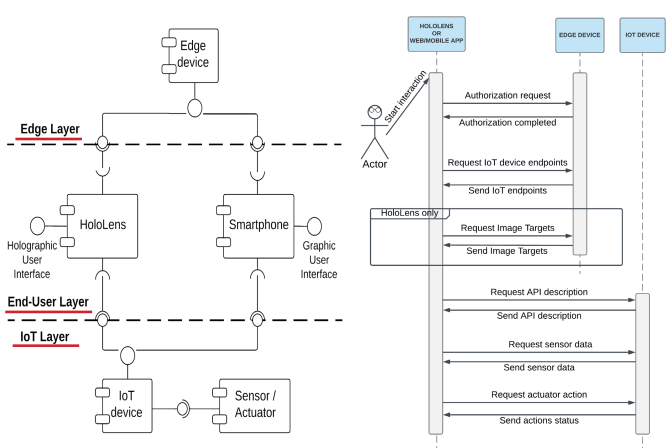

Fig. 2. System Representation

A. IoT Layer

This layer handles the communication with sensors and actuators connected to different embedded devices. The available physical devices within range are a part of this layer and share their capabilities with the end-user layer via a simple web protocol. Hence, an initial setup phase is required to reveal the available sensors and actuators connected to the system and associate them with a machine. To do so, a semantic representation of the device functionality is exchanged with the end-user layer and used for automated build of holographic interface.

Implementation details. For this layer we used multiple embedded devices. The backend software to communicate with the other layers was developed by combining Python and Raspberry Pi. The GPIO library was used to handle sensors and actuators, and the flask framework was used for server management and interaction over the network.

B. End-User Layer

The end-user layer is the core of our system and handles the organization and spatial recognition of the holograms. It is built as an event-driven application based on Unity and is composed of four main modules. The *UI Manager* is responsible for automated generation of holographic interfaces based their semantic representation. The *Event Manager* manages the information about IoT devices and processes device detection and interaction events to update the UI Manager. The *Server Manager* is the core communication module and is responsible for all data exchanges between system devices. In addition, the Server Manager loads the recognition models and semantic data from IoT devices. The *Semantic Module* is the data layer of the application and stores information about IoT devices and their virtual representation plus the specifics available functionalities.

Implementation details. The end-user layer was implemented in C# with Mixed Reality Toolkit libraries, and it runs directly on HoloLens. Object detection and tracking is implemented with the Vuforia AR SDK.

C. Edge Layer

The physical interaction between the headset and a machine happens only when the user is in direct proximity to the relevant IoT sensor; we decided to reflect this feature in our system design. In particular, instead of storing all the information regarding a group of smart devices on the cloud, we collected configuration and capabilities of the smart devices at the edge. Hence, to access the holographic interface of a specific machine, it is necessary to be in its proximity. This makes sense because the necessity of visualizing a 3D model of a physical objects arises only when we are close to it.

The deployed edge device is responsible for a cluster of IoT nodes in proximity: it stores IP endpoints and object recognition models of smart devices that are used by the end-user layer.

Implementation details. The backend application running in this layer to store information about the devices in the network was developed as a combination of Node.js and MongoDB.

III. Evaluation

We conducted two types of evaluation: user study and application benchmarking. For the experiments, multiple embedded boards equipped with sensors and actuators were installed in a room. Each actuator or sensors controlled a specific component of the machine (e.g., a spinning gear). Physical manipulation of these devices changed the state of specific components inside the 3D model of the machine. The system starts in an unstable state and the goal was to bring the machine to a stable state opportunely tuning different components (e.g. align spinning gears, control their speed, avoid overheating). Users were notified about the task completion through the interface they were using: either HMD and holograms or a SCADA-like web interface and a tablet. When using the HMD, the hologram changed in real-time according to the user inputs. In contrast, the web interface only provided textual feedback.

A. User Study

The usability test was aimed at answering two distinct questions: **Q1.** *How do participants receive the usage of the holographic technology?* and **Q2.** *How do holographic interfaces fare compared with standard ones?* The experiment was completed in four days and involved 22 participants (19 males and 3 females). Each user interacted with the system for 20 minutes. Most participants had a background in computer science and previous experience with AR or VR headsets. Only 18% of participants had previous experience with HoloLens.

During our usability test, the participants were asked to firstly get used to the HMD and the holograms technology and then evaluate the holographic interface interaction with our application. After the test, the users were asked to fill out a questionnaire. The questionnaire about design-oriented development was based on the study reported by Wich et al. on usability-evaluation questionnaires [10].

We observed that users feel uncertain about the convenience and feasibility of integrating holograms in their daily life. However, there is indeed a trend showing that holographic interfaces are in general more attractive as participants had a positive experience with the holographic manipulation. These results are summarized in Figure 3. New users grew accustomed to the holographic interface quickly and felt more confident after learning the basics. To summarize, the major concerns expressed by the users regarding HMDs were: inaccurate gesture recognition windows, narrow field of view, abrupt gaze pointer and headset weight and placement.

For the second part of the study, users were asked to compare their experiences of the two interfaces and express their preference. Result are shown in Figure 4. The majority of the participants preferred the holographic application (despite the manifold issues experienced with HoloLens) and stated that interacting with the SCADA-like web interface required greater effort. Only a small percentage of the participants expressed their scepticism regarding the holographic interface asserting to not feel confident during the interaction with holograms.

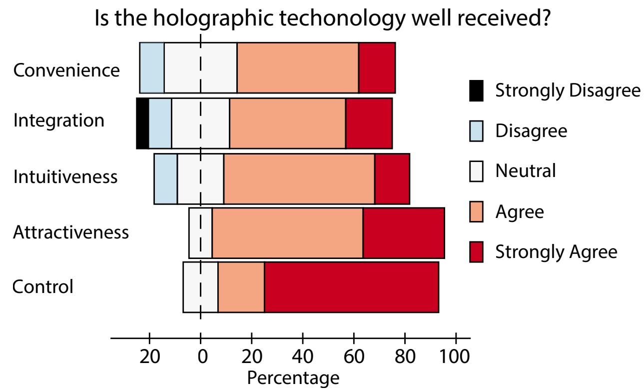

Fig. 3. The holograms technology is generally well received

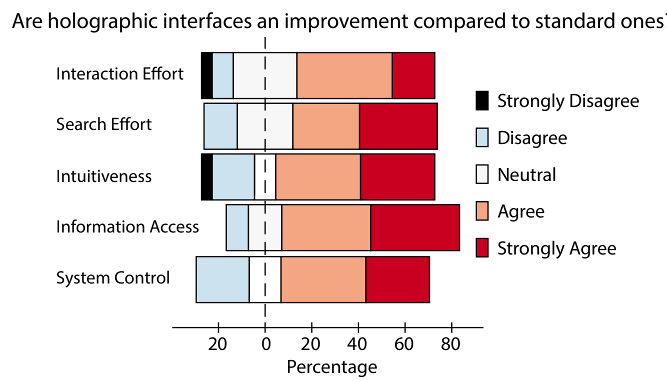

Fig. 4. Holographic interfaces proved to simplify manifold interactions compared to traditional ones

B. Performance Analysis

Figure 5 shows preliminary performance results of our application (average of 10 iterations) retrieved with Windows Performance Recorder and successively analysed with the Windows Performance Analyzer. The measurement granularity is one data-point/s. System power consumption represent the amount of power complexly used by Hololens while SoC power consumption amounts only for CPU, GPU and memory. All values (except FPS) are represented as a percentage of the total available resource. Power consumption was definitely high during all our experiments, the application posed a lot of stress particularly on the GPU leading to high SoC power consumption values. Considering the device's autonomy of 113 minutes and its charging time of 1 h, we conclude that either the battery should be optimized or developers must find a good trade-off between application functionalities and battery life. CPU utilization was reasonable with peaks caused by the Vuforia image recognition process, which includes the loading of recognition data and IoT components discovery. Thus, based on values of the processor load during the interaction, we conclude that the HoloLens has sufficient CPU power for image recognition tasks. GPU usage is heavily affected by the UI panel rendering, which also influences placement of and interaction with holograms. FPS were definitely acceptable with an average of 48 and the usability testing showed that even with just 20 FPS (during complex holographic visualizations) the user experience was not compromised.

In our tests, we assessed that the Hololens has overheating. We used a ThermalSeek IR camera to monitor the device temperature over time. After an average of 30mins, it reached a peak of 43.3° Celsius (our lab temperature was 29° Celsius) and constantly switched to a *cooldown* state effectively preventing any kind of interaction. Hence, the device is not designed for prolonged utilization and the cooldown state breaks the user experience.

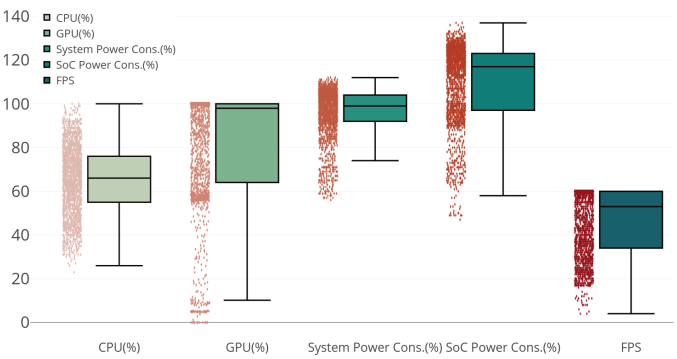

Fig. 5. Holographic application performance

IV. Related Work

There have been multiple attempts to integrate AR with smart devices. In fact, augmented reality was recently announced as one of ideal interfaces in IoT; its layer offers an abstraction that provides a simplified view on smart things and hides all irrelevant technical details from users [11]. Factory of the Future [12] describes factories as the perfect use case for the IoT object manipulation through augmented reality. It introduces a multi-modal and multi-client system for a huge factory which supports workers on their workplaces and provides a control interface through augmented reality device. A similar system which is based on the mobile augmented reality is described in [13]. This system is completely controlled with a smartphone carrying out both object recognition and detection.

Enhanced Real-Time Machine Inspection [14] is an inspection system for an industrial worker that improves the worker's productivity, safety and effectiveness exploiting Hololens and AR. Similarly, [15] analysed the users' reaction and feedback on various AR interfaces in order to come up with an unique design that is natural and fits to a diverse category of users. However, the authors of that study do not describe the entire architecture of the prototypes and do not provide any information about communication protocols, background logic, and supported devices, making it difficult to duplicate.

V. Conclusions

This study presented a hologram-based framework for the manipulation and control of IoT devices in industrial settings. We built an end-user centered architecture in which multiple IoT device were managed by a single edge board and controlled via holograms. We evaluated our system via a user study comparing the hologram to the conventional SCADA web application. The results revealed that users favor interaction via hologram. Our system benchmarks also revealed the limitations of existing HMD devices that deserve future investigation from the community.

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