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Augmented reality for machine monitoring in industrial manufacturing: framework and application development

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Abstract

Enhancing data visualization on the shop floor provides support for dealing with the increasing complexity of production and the need for progressing towards emerging goals like energy efficiency. It enables personnel to make informed decisions based on real-time data displayed on user-friendly interfaces. Augmented reality (AR) technology provides a promising solution to this problem by allowing for the visualization of data in a more immersive and interactive way. The aim of this study is to present a framework to visualize live and historic data about energy consumption in AR, using Power BI and Unity, and discuss the applications' capabilities. The study demonstrated that both Power BI and Unity can effectively visualize near-real-time machine data with the aid of appropriate data pipelines. While both applications have their respective strengths and limitations, they can support informed decision-making and proactive measures to improve energy utilization. Additional research is needed to examine the correlation between energy consumption and production dynamics, as well as to assess the user-friendliness of the data presentation for effective decision-making support.

1. Introduction

In today's industrial manufacturing environments, data plays a critical role in driving efficiency, productivity, and profitability [1]. To utilize data, enabling digital technologies such as the Internet of Things (IoT), big-data analytics, and augmented reality (AR) are being developed and designed for implementation in production environments. These technologies are part of the field of visual computing and comprise the collection, analysis, and presentation of visual data using computers [2]. Visual computing is applied to enhance the analysis and presentation of production data, thereby accelerating the improvement process. Various computer-based media solutions can be used to present information, aiding operators in their decision-making processes [3].

Enhancing data visualization on the shop floor provides support for dealing with the increasing complexity of production and for monitoring emerging goals such as energy efficiency. It offers tools for root cause analysis, enabling personnel to make informed decisions based on real-time data displayed on user-friendly interfaces. These interfaces can be critical for efficient problem identification and resolution, and can ultimately lead to reduced downtime. Given the increasing demands of production processes, there is a need to examine how to utilize digital technologies for enhancing productivity. AR provides a promising solution to this problem by allowing for the visualization of data in a more immersive and interactive way.

AR allows the user to see the real world with virtual objects superimposed upon or composited with the real world, it could be images, audio, video, touch, or haptic sensations [4]. By making the physical world more transparent, it allows personnel to monitor processes and gain knowledge about among

others deviating machines to act with the right measures to increase production efficiency. The interest for using AR for data visualization within the industry has increased lately due to advancements in hardware and software. Common hardware technologies used for implementing AR are head-mounted displays (HMD), handheld displays, see-through displays, or projectors. Additionally, through the development of computer-aided technologies such as sensors and interactive AR visualization software (such as Power BI and Grafana), analysing and exploring large amounts of data through visualization becomes more widespread on a shop floor level [5, 6]. Besides the widely used visualization platform Power BI in the industry, other possibilities of visualizing dashboards using AR can be implemented by custom applications and open-source tools using software such as Unity [7].

Despite the availability of new visualization hardware and software, data and the traditional software tools available to the production personnel are oftentimes insufficient to analyse the process systematically and holistically [1]. In fact, many data displays in production are still based on whiteboard and paper. This could stem from the fact that visualizing real-time process data in AR is challenging and time-consuming, particularly when working with multi-source data [8]. The task of effective data visualization in production is further complicated by the immeasurable amount of data collected from the processes, generated by increasingly sensorized hardware in production. Capable software tools are required to process and display the data, but currently no one-size-fits-all standard exists. Studies suggest the need for adaptable frameworks, often employing open-source tools, to achieve real-time visualizations effectively [7, 9, 10]. Therefore, visualizations rely on data pipelines that allow connections to multiple databases and manufacturing systems. With the continuous development of software and hardware, there is a need to examine the suitability of different applications for data visualization utilizing augmented reality.

This study focuses on the utilization of AR for visualizing electricity consumption of production machines. An increasing number of individuals use mobile applications in their households to monitor electricity consumption and pricing. These applications rely on data obtained from smart meters to show the consumption patterns and associated costs of different appliances. Consequently, users are empowered to comprehend and modify their behaviors in order to reduce both electricity usage and costs [11]. Within industrial manufacturing firms, the energy consumption is significantly higher than that of an average household. However, partly due to the historically low energy prices, these firms often do not employ smart metering and visualizations for enhancing energy efficiency at the shop floor level [11, 12]. While internal reports on department-level consumption exist primarily for billing purposes, they are not utilized for production improvements. Consequently, the integration of new technologies can assist in evaluating energy consumption within manufacturing processes by presenting energy dashboards to personnel.

The primary objectives of the study are to develop data pipelines that can be transformed into visual components within an energy dashboard solution, utilizing two AR applications, namely Power BI and Unity. Therefore, the main research contribution is two-fold:

(i) Presenting data pipelines and visualizing energy dashboards on production machines with two commonly used AR applications; Power BI and Unity.

(ii) Comparing the two visualization applications based on this use case.

2. Data visualization with augmented reality

This study was conducted at a pilot automated assembly line used by the case company within the automotive industry to showcase new production technology. The study utilized electricity consumption data from three industrial robots that were used in the assembly process of a steering wheel at station one and a front wheel at station two. At the first station, one robot picked the steering wheel from a container and positioned it, while another robot's arm, equipped with a nutrunner, magnetically picked a screw to tighten the steering wheel. At the second station, a third robot picked a front wheel, placed it onto the wheel hub, and subsequently secured it in place using a screw.

The development of automated data flows that feed the dashboard solution was guided by the findings presented by Schmitt et al. [10]. To meet the specific requirements of this study, a Design Science Research approach [13] was employed to further adapt the foundation provided by this prior work.

2.1. Hard- and software requirements

To support the AR visualization, Microsoft HoloLens 2 and Apple iPad Pro 12.9, which offer mobile AR support, were selected as the AR hardware. Three ECR140D energy meters from Hager were employed to measure the energy consumption of the robots in the assembly line. The electricity readings were consumed and forwarded through the connection with a Programmable Logic Computer (PLC). The open-source Internet of Things (IoT) platform Node-RED was utilized for the operational technology (OT)/information technology (IT) gateway connection. The data was then transmitted to a Structured Query Language (SQL) database, where it was stored in the form of tables.

The choices for the two AR visualization platforms were primarily based on their compatibility with the AR devices. Furthermore, one application was chosen based on the case company's existing data visualization solutions (Power BI), while the other application was chosen based on its 3D prototyping and development capabilities (Unity). Power BI is already partially in use at the case company's shop floor, whereas Unity, a tool for creating graphical applications on several platforms such as Windows, iOS, and Android, is primarily used for prototyping and testing purposes within the company.

2.2. Data pipelines

To implement energy dashboards effectively in various applications, it is necessary to establish suitable data pipelines that

enable the collection, processing, storage, and visualization of energy data generated by production machinery. In this study's test production line, electricity meters are connected to three robots, referred to as UR, Yaskawa, and ABB, to measure their respective power consumption. These meters are then linked to a Programmable Logic Controller (PLC), which transmits the collected values to an OPC UA server. An OPC UA client on the open-source platform Node-Red connects to the OPC UA server, and upon connection, the data is processed by converting the power value to kilowatts and adding a timestamp. This processed data is then sent to an on-premise SQL database on a minute-by-minute basis.

Power BI natively supports connection to the SQL database. The Unity application consumes the data from the same database, but a few adjustments were needed. The data is retrieved from the SQL database back through Node-Red, where various filtering methods (to display consumption over night or during operating hours) are applied. This filtered data is then shared through an exposed Representational State Transfer (REST) Application Programming Interface (API), to which the Unity client can connect. Although a direct connection from Unity to the SQL server is possible, it was not implemented due to security concerns. Within Unity, Microsoft's Mixed Reality Toolkit (MRTK) was used with its out-of-the-box AR building blocks for data visualization. A general overview of the hard- and software used is presented in Fig. 1.
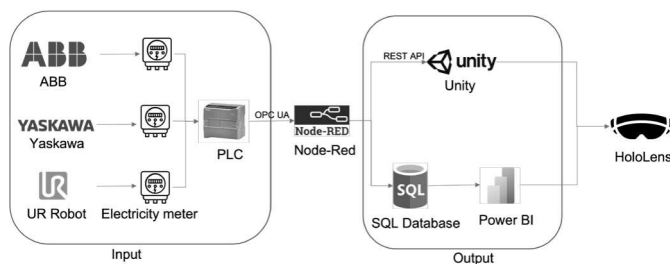

Fig. 1. Data pipeline infrastructure.

3. Results

3.1. Deployment with the software Power BI

The dashboards were created utilizing the built-in visualization functions provided by Power BI. The Power BI dashboards consisted of three distinct types of visualizations. The first type visualized the total energy consumption of each machine overnight. The second type displayed the aggregate energy consumption of each machine during operational hours. The third type was a time series chart and presented near real-time energy consumption data for each machine over time. All three visualizations are depicted in the monitor dashboard version in Fig. 2. The Power BI also supports presentation on hand held AR and head-mounted AR. The reports for the AR media were created using Power BI Desktop, and published to a cloud server using Power BI service to make the reports accessible over the internet.
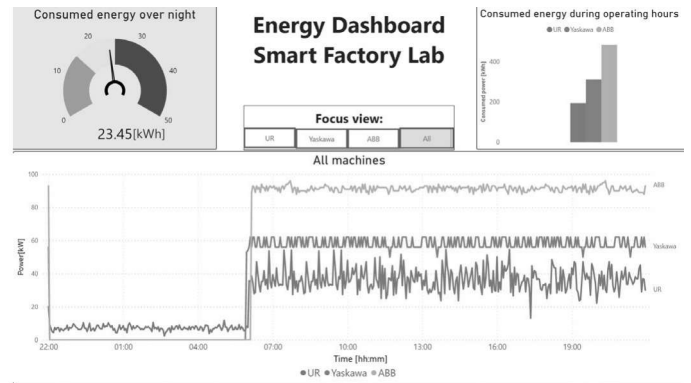

Fig. 2. Screenshot of the dashboard displayed using Power BI Desktop.

A. Tablet

For the tablet solution, the Power BI application for iOS was used, which supports AR via the usage of QR codes on tablets and phones. Each diagram was assigned a QR code and placed throughout the assembly line. The QR codes were created in the application, printed, and put up on the safety fence surrounding the assembly line. By that, the user can scan the code with the tablet using the application that would create an AR object on that location. Each QR code is generated for a specific dashboard or report within the Power BI service. If one wants to share multiple dashboards or reports, one needs to generate a separate QR code for each. An example of a diagram is shown in Fig. 3.

Fig. 3. Dashboard displayed using Power BI for iOS and mobile AR.

B. HoloLens

The Power BI application for HoloLens was used for the deployment of the dashboard to the HoloLens. Similar to the tablet, specific reports were created in Power BI Desktop for the HoloLens application. The dashboard comprised four distinct screens. The first screen, located at the entry of the assembly line, displayed both an energy gauge and a bar chart depicting the total power consumption across all robots. The remaining three screens were located above the respective robots, showing the power consumption for the corresponding robot. Fig. 4 shows the screens' placement in close proximity to the robots. The dashboard holograms were positioned using HoloLens gesture controls. Once the dashboard hologram is in position, the "anchor" gesture creates a spatial anchor for the hologram. The

hologram will remain in the same position, even if you move around or turn off the device.

Fig. 4. Dashboard displayed using HMD AR.

3.2. Deployment with the software Unity

Unity's XR Plugin Management System can deploy to most mainstream AR/VR devices, including both hand held and head-mounted AR devices. As this study's target device is HoloLens, the Unity project is configured using the "Universal Windows Platform (UWP)". Additionally, in this project, elements from the Mixed Reality Toolkit (MRTK) by Microsoft are used. The visualizations are built with help of the Unity package "Graph and Chart". Similar to the Power BI dashboards, the visualization in Unity contained a bar chart showing the aggregated energy consumption by each machine, and real-time streaming line graphs showing the live consumption of each robot. Visual Studio is used for the deployment to HoloLens.

Initially, Computer-Aided Design (CAD) files are imported into the scene showing a virtual representation of the automated assembly line, including the three robots. This allows the visualization of data on a fully virtual version of the line (Fig. 5) as well as superimposing holograms on the physical version (Fig. 6) . To display data in Unity that is obtained through a REST API, a combination of Unity's UI system and the scripting language C# is necessary to acquire and parse the data. The Graph and Chart package offers charts and prefabs that can be applied to the charts. In this study, a bar chart and three line graphs were utilized. A script using UnityWebRequest to retrieve the data is attached to the GameObjects in the scene. The script retrieves and parses the data which is then used to populate the charts. The updating frequency is set using the web request frequency and can be adjusted down to the second level or aligned with the database's storage rate. Lastly, two MRTK components are added to each GameObject; the object manipulator component allows the elements to be moved and rotated, while the Near-InteractionGrabbable component enables them to be grabbed. Two distinct scenes are created, one for the fully virtual version and one for the augmented display.

A. HoloLens
Initially, a UWP build of the scene is constructed in Unity. The
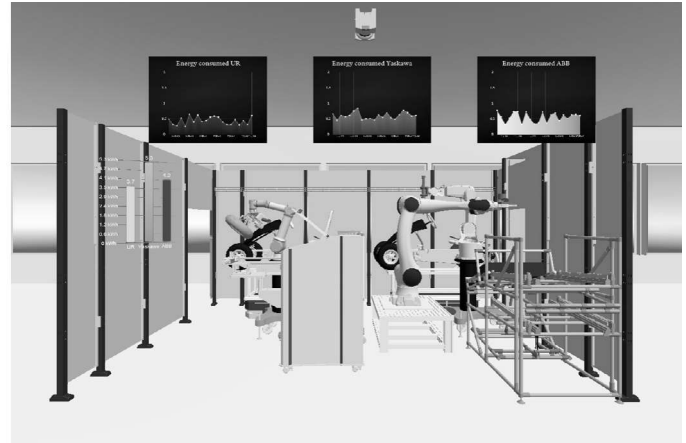

Fig. 5. Virtual display of the dashboard in Unity.

resulting application is compiled in Visual Studio and deployed onto the HoloLens. The procedure of building and deploying via Wi-Fi connection requires an IP configuration inside Visual Studio. Once the project is deployed onto the HoloLens, the user can interact with the elements using the hand rays, which enable users to target, select, and manipulate the elements. The augmented displays hovering over the robots are visible in Fig. 6.

Fig. 6. Augmented display of the dashboard using HoloLens.

4. Discussion

4.1. Augmented reality applications for data visualization

The selection of hardware and software for the dashboard infrastructure was influenced by various factors, where also different systems and software could be used. One of the key considerations and constraints was the availability of AR hardware, along with the company's preference for using Power BI as the standard data visualization solution. The resulting data pipelines were adjusted from previous work from Schmitt et al. [10]. For this, mostly open-source tools and standards such as Node-Red, OPC UA, REST APIs, and Unity packages were used, tools which usefulness have been demonstrated in other studies [7]. These pipelines enabled the automatic collection and updating of sensor data related to the electrical energy con-

sumption of three different industrial robots operating in an assembly line, which could be visualized on hand-held and head-mounted AR hardware using the AR applications. Both applications presented the energy consumption of the entire assembly line and individual machines, however, they required different approaches.

4.1.1. Power BI

Power BI is commonly used for visualization purposes within the case company and the industry as a whole, and allowed for native AR support. The following advantages and disadvantages were encountered during the execution of this study:

A. Advantages

Power BI has several features suitable for augmented reality applications, such as native support for connecting to various data sources and integrating with other Microsoft products such as tablets and the HoloLens. As one of the most widely used visualization platforms, it is easy to use and to navigate its interface. There is need of only higher-level programming, or none whatsoever. This makes it easy to explore the data and design charts with the many integrated basic and advanced visualizations and filters. Power BI has good processing capabilities and is able to query over large tables. Another main advantage is the community and online resources around the platform, providing substantial support when encountering problems.

B. Disadvantages

In contrast, the support for AR in Power BI appears to still be in its infancy, with a laborious and time-consuming setup. Frequent software failures are encountered, e.g. when loading report pages from the tool belt of the HoloLens or when reports disappear from the field of view, further complicating the dashboard setup. Additionally, the AR features of Power BI lack sufficient support in the Power BI community when encountering such issues. Furthermore, the reporting updating frequency is limited to 10 minutes when hosted on a cloud server. Moreover, the software's usability is designed for Microsoft's technology stack, which may not be suitable for organizations with diverse technology infrastructure. This limitation was encountered when attempting to use the time-series database Influx DB as an alternative data source, for which no plugin was available.

4.1.2. Unity

Unity is a game engine that has expanded its functionality beyond game development. Although it has been frequently used within the company for prototyping projects, this study represents the first examination of its use for real-time data visualization in production.

A. Advantages

Unity offers a wide range of customization through its various packages and features tailored to data visualization, including those for AR, such as Microsoft's MRTK. This allows greater design freedom and the ability to create unique data visualizations with customizable colors, textures, and lighting effects. Furthermore, Unity enables comprehensive modeling of entire production line layouts, and superimposing live data on top of the virtual model, as depicted in Fig. 5, which can be used for

remote monitoring of the process. Unity's refresh rate is close to real-time, and it supports numerous devices, including desktops, hand-held devices, and HMD AR.

B. Disadvantages

In order to fully utilize Unity's capabilities for data visualization with AR, manual programming with C# is necessary, which may not be suitable for non-technical users. Even those who are familiar with game engines or programming may need to invest more effort with Unity. Furthermore, as the platform is not primarily designed for data processing, this part was shifted upstream onto the OT/IT gateway Node-Red, which forwards already pre-computed values to Unity. Additionally, deploying Unity projects on devices requires more computing power.

4.2. Comparing the two applications

Both AR applications allow for data visualizations in augmented reality and for spatially anchoring the AR elements within the physical environment. However, the functionality of the two applications differ significantly. Firstly, Power BI offers a user-friendly interface with interactive visualizations and tools that allow non-technical end-users to create their own reports and dashboards. Conversely, Unity requires a greater amount of manual programming effort and is thus not well-suited for non-technical personnel. Even creating simple bar charts in Unity that display data from a REST API requires familiarity with both Unity's UI system and C# programming. Although it lacks some of the data visualization features that specialized tools like Power BI offer out-of-the-box, Unity offers a wide range of packages, graphics, and animation features that provide more design freedom. Unity also offers a higher updating frequency for dynamic and near-real-time data visualization. In summary, Unity can offer powerful data processing capabilities for technical users, while Power BI can be used for user-friendly displays where little customization is necessary or desired. Additionally, Unity can be used for the development of digital twins, which is an interesting and emerging research direction [8]. A digital twin allows for managing the physical world through the virtual world via a two-way communication.

4.3. Energy visualizations in production systems

The three different types of visualization shown in this study are believed to be able to lead to better energy utilization in production. The first type, the visualization of the total energy consumption of each machine overnight, gives feedback on whether the machines consume energy during periods when the machines are not in use and hence have not been shut down (i.e., waste). The second type, displaying the aggregate energy consumption of each machine during operational hours, allows the user to identify which machine is the largest consumer of energy. This information can be used to identify potential areas for optimization or replacement of less efficient machinery. The third type, a real-time time series chart presenting power consumption for each machine, allows the user to get an understanding of the behaviour of the machines. It can help detect irregular behaviour during production and non-production time

enabling identification of inefficiencies and corrective action. Overall, by providing a comprehensive visualization of the consumption across the assembly line, it can enable more informed decision-making and facilitate proactive measures to improve energy utilization. The visualizations used were gauges, bar charts, and time graphs, while other methods of visualizing are possible such as the ones highlighted in the works of Masoodian et al. [11]. Various electrical parameters such as voltage and current were also available and could have been used further.

4.4. Future research

The information presented in this study predominantly focused on descriptive statistics related to energy consumption, including average energy usage during production shifts. However, a crucial subsequent step would involve integrating this data with productivity data derived from Manufacturing Execution Systems. Such integration would facilitate the calculation of energy consumption per unit produced, which serves as a more meaningful metric for monitoring progress towards energy efficiency within the manufacturing company, as opposed to using absolute energy consumption measurements. The introduced dashboards also enable the visualization of real-time power consumption per machine, unveiling fluctuations in equipment usage during different machine states, as described in ISO 14955 [14]. This information can assist in identifying the energy consumed during value-adding activities, such as processing, in comparison to non-value-adding activities like idling, downtime, and repairs. Analyzing this data across all machines may potentially pinpoint specific time-frames and operation modes associated with increased energy consumption, thus providing valuable insights for optimizing energy efficiency within the production process.

5. Conclusion and future work

The use of augmented reality for data visualization is gaining importance in industry as it allows for better understanding of production processes in an interactive and immersive way. By placing data directly in the user's field of view, AR can help production personnel to identify trends more quickly and accurately, leading to more informed decision-making. This paper presents a framework for AR data visualization using Power BI and Unity, and offers guidance to practitioners in choosing and designing AR applications for production. Power BI is recommended for non-technical personnel requiring a user-friendly tool with a large variety of data visualization features, while Unity is better suited for technically proficient personnel to create interactive, close-to-real-time, and customizable data visualizations in AR. Further studies are needed to investigate the integration of both energy and productivity data to gain a deeper understanding about production dynamics. Additionally, the usability of the suggested framework and applications in an industrial setting requires further investigation.

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