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Design and Implementation of a Marker-Based AR-Enabled Tool Tracking System for Manufacturing Manual Operation

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ABSTRACT

Manual operations exhibit variability and are subject to human errors, which can lead to unexpected delays or quality issues. In addition, traceability of manual processes typically relies on operators' interactions with HMIs, which can also be inconsistent. Research suggests that augmented reality (AR) can be used to enhance the effectiveness of manual operations by enhancing operator guidance. The research presented in this paper adopts a holistic approach combining manual operation monitoring and operator feedback capabilities. The DAMPO (Digitally Augmented Manual Process Optimisation) developed at the University of Warwick, UK, is used to support both low TRL level research and direct engagement with industry on the development of human-centric manufacturing solutions. The DAMPO system implements both process monitoring capabilities and advanced operator guidance interfaces in view of enabling process traceability and no-fault forward capabilities. Manual assembly of safety-critical systems of seating components for the automotive industry is the use case application for this study. This production-ready solution is tested and evaluated on a replicable production cell using real product and real manual assembly sequences.

Keywords: Augmented reality, Human-machine interaction, Manufacturing process traceability

INTRODUCTION

Although automation and robotics are widely implemented in the manufacturing industry, assembly tasks and rework processes that are complex or require a high level of flexibility and adaptability are still carried out manually (Mourtzis, Zogopoulos and Xanthi, 2019). By nature, manual operations exhibit variability and are subject to human errors, which can result in production delays, process deviations and quality issues.

The Industry 4.0 paradigm has promoted the development and deployment of digital solutions to support the manufacturing workforce (Longo, Nicoletti and Padovano, 2017). Solutions that support manual operations generally focus on either or a combination of two types of functions: providing guidance to the operator to complete a process (Büttner and Röcker, 2017; Álvarez et al., 2019), and/or monitoring the process for validation and/or traceability purposes (Lou et al., 2022; Yan and Wang, 2022).

Research suggests that augmented reality (AR) technology can contribute to enhancing human-machine interactions by providing operators with a seamless digital bi-directional interface to physical systems (e.g., product or production systems). Existing research related to the development of AR-based solutions for manufacturing focuses on supporting specific use cases such as training (Wang et al., 2022), maintenance (Dvorak, Josth and Delponte, 2017) and system configuration use cases (Álvarez et al., 2019).

Traceability of manual operations is intrinsically more challenging to achieve than for automated processes, as it typically relies on the operator consistently providing direct input e.g., via HMI/operator interaction. Solutions have been implemented to monitor specific operations (Lou et al., 2022) and also automatically characterise the operation being carried out (Günther, Kärcher and Bauernhansl, 2019). However, the consistency and accuracy required for deployment and operation in a real production environment are difficult to achieve.

The research presented in this paper adopts a holistic approach to the digitisation of manual operations, combining process monitoring and validation, and operator feedback and guidance capabilities. The DAMPO (Digitally Augmented Manual Process Optimisation) system results from the integration of a) a marker-based tracking solution used to track the pose of tools used by operators, b) an information-rich and highly interactive user interface deployable on screen-based and AR head-mounted displays as well as normal screens, and c) of a data capture, management and processing solutions that support real-time data collection and processing, and the provision of feedback information to the user throughout the process.

BACKGROUND RESEARCH

Traceability of Manual Process

A manufacturing process that involves human activities could lead to unwanted incidents, for instance, quality issues and unexpected delays (Rodriguez et al., 2015; Mura, Dini and Failli, 2016). Reducing human errors by improving the level of traceability of manual processes could enhance production efficiency (Mura, Dini and Failli, 2016). However, capturing manual process data is challenging as the data collected is not guaranteed to be comprehensive or accurate (Standfield and Gračanin, 2021).

There are different approaches to tracking manual operations and accuracy varies depending on the approach adopted (Fischer et al., 2016; De Feudis et al., 2022). High tool pose (i.e., position and orientation in space) tracking accuracy is required in order to consistently validate specific processes (e.g., specific and precise positioning of the tooltip). Unlike marker-less tracking methods (e.g., feature-based pose estimation (Seppala et al., 2022)), the tracking of markers allows precise pose estimation (Lou et al., 2022). The DAMPO system integrates an NDI Polaris Vega XT optical tracker to track markers made of reflective spheres arranged in various patterns. NDI systems are used in surgical settings (Teatini et al., 2019, 2021) and provide sub-millimetre accuracy and high-frequency tracking, which is an important factor for tracking fast operations and for implementing near real-time user feedback functions.

User interfaces and interactions

DAMPO offers an AR-based user interface for operator guidance. Various research projects have demonstrated that MR can minimise the barrier between physical and digital worlds. It is nowadays widely used in various industries including architecture, healthcare and manufacturing (Teatini et al., 2021; Tan et al., 2022). It is suggested that AR is one type of MR that provides virtual content on real objects in a physical environment seamlessly (Carmigniani et al., 2011; Chun and Lee, 2012; Juraschek et al., 2018). Existing literature identifies some key elements of AR. Tan, Xu, Li and Chen summarise from previous literature that AR consists of i) real-time interaction, ii) tracking and positioning and iii) composite image (see Figure 1). In the following subsections, implementation of a head-mounted display (HMD) and three-dimensional environment that helps achieve AR is discussed.

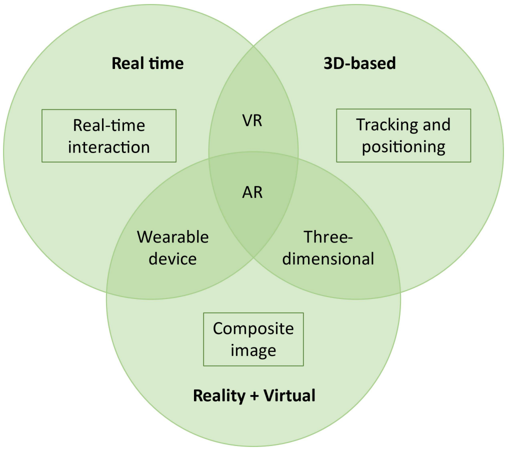

Figure 1: Components of MR (Adapted from Azuma, 1997; Tan et al., 2022).

Wearable device: The use case assembly process for DAMPO requires hand-free operation, as the operator needs to handle both the product (i.e., operate the pallet rotation and tilt mechanisms to access working points) and the tool itself. Unlike traditional screen-based human-machine interfaces (HMIs) or tablet-based AR, Head Mounted Displays (HMD) allow users to experience handsfree, interactive and collaborative AR in real-time (Carmigniani et al., 2011; Tan et al., 2022), and thus can enable more efficient assembly processes (Mura, Dini and Failli, 2016; Hoover et al., 2020). Some head-mounted systems allow interactions through tracking of body gestures and voice (Kress, Saeedi and Brac-de-la-Perriere, 2014) further enhancing hands-free capabilities.

Three-dimensional environment: There are various methods to define the pose of AR content in the virtual environment (Chun and Lee, 2012). Marker-based AR uses fiducials to calculate the relative pose of the device camera and the physical scene, which is needed to display the AR content in the required position and orientation (Siltanen, 2012; Romli et al., 2020). The fiducial can be a 2D graphic (e.g., QR code) or a 3D object (Siltanen, 2012; Cheng, Chen and Chen, 2017; Romli et al., 2020). Markers need to be fully or partially contained in the camera field of view for the AR content position and orientation to be updated continuously.

Research Gap

Research shows that AR could be beneficial at various stages of manufacturing processes (Bottani and Vignali, 2019). AR can be used to provide instant feedback to operators (Rodriguez et al., 2015; Alves et al., 2021). However, MR solutions appear to be used mainly to support training, system set-up and maintenance operations (Quint, Sebastian and Gorecky, 2015; Juraschek et al., 2018), and there is limited research currently focusing on providing solid technical solutions to support in-production scenario (Bottani and Vignali, 2019).

The use of MR and AR to support in-process operation poses some challenges, including suitability of existing HMDs for extended periods, hardware reliability, as well as consistency and stability of the real-world pose tracking and AR layer display, which can significantly impact the usability of AR solutions (Brizzi et al., 2018). The research presented in this paper proposes a solution that combines a) process monitoring and validation based on the tracking of tools used by the operators, b) augmented work instructions, which can be delivered in various forms depending on the use case requirements and constraints, i.e., via AR HMDs (HoloLens in this case), screen-based AR (use of a tablet camera/screen), or via a classic screen-based HMI with the addition of rich and interactive 3D content.

MARKER-BASED TOOL TRACKING SYSTEM OVERVIEW

Functional Overview

The DAMPO system comprises several elements: 1) an NDI Polaris Vega XT sensor mounted above the work cell at a height of 3m to ensure the entire seat is contained in the pyramidal detection volume. 2) A tool sleeve with different marker patterns on the four sides of the tools to allow tracking of tools regardless of their orientation as one marker is always exposed to the NDI sensor's IR cameras. 3) An additional marker is mounted on the pallet that supports the product so that the position of the tool can be tracked relatively to the pallet. This is required to ensure tracking consistency and accuracy regardless of the pallet stop position, inclination, or rotation. The DAMPO software solution is composed of 4) the real-time data capture and management module, which ensures a continuous log of the tool pose data composed of timestamp, XYZ coordinates and orientation quaternion (4 values). Each cycle data is further linked to a metadata set that includes station_ID, product_Type and product_ID. 5) A process database contains a) a definition of working locations for each product type (obtained from scanning the bar code on the pallet) and the associated pose that the tool should be in when operating at these locations, b) a sequence in which these operations must be carried out (e.g. bolt tightening pattern) so that in addition to each individual steps, the whole assembly sequence can be validated. 6) The DAMPO systems implement various forms of HMI (i.e., screen-based 3D content, screen-based AR content, HMD-based AR) that all provide a) operator guidance as the location of the next work position and b) operator feedback, which include product type, process steps completed, as well as other controls allowing the operators to input a redo-step, skip-step, product-fault action.

Database, Data Management and Data Pipeline Design

The database system is composed of two sub-systems a) pose data capture, management and processing and b) human-machine interface (HMI) (see Figure 2). The host computer fetches the real-time data from the NDI sensor at 10 Hertz, attaches the metadata and stores the pose data corresponding to a cycle into a Time Serie database. The HMI sub-system focuses on creating high-interactive user interfaces for operators and/or line supervisors.

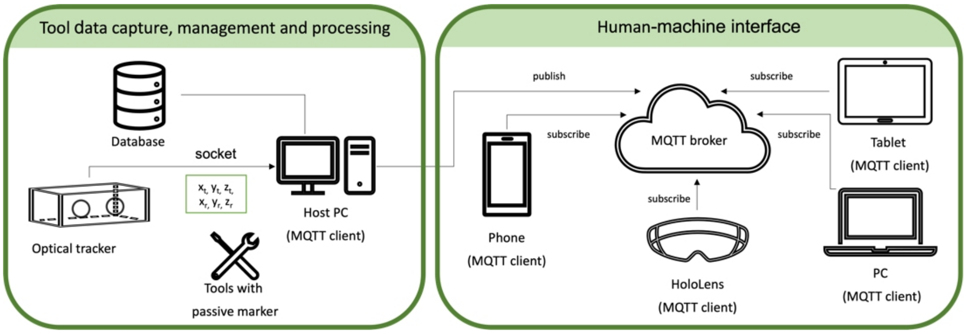

Figure 2: System architecture and data flows of the DAMPO tool tracking system.

Portable devices (e.g., laptops, tablets, HMD) subscribe to the MQTT broker to obtain the live data and/or historical data from the data capture system and display process-related information (i.e., work instructions and validation results, tool path for previous cycles).

System Setup

The elements supporting pose tracking are shown in Figure 3. The use case application requires a 3 mm accuracy in tool pose detection in order to differentiate the closest working positions. This is within the NDI sensor tracking accuracy which is 0.12 to 0.15 mm Tools must be registered to the system by performing pivot calibration to derive the pose of the tooltip. The pallet-mounted marker must also be registered to the system as a global marker. Thus, the output of the tool pose is calculated with reference to the global marker.

Figure 3: Pallet-mounted marker (left), NDI Polaris Vega® XT optical tracker (middle), tool-mounted passive markers (right).

To implement hands-free AR-enabled HMI for the use case, Microsoft HoloLens 2 is used. The sensors (e.g., IR cameras, IMU, depth) equipped in the device provide capabilities to deploy high interactive and hands-free features (e.g., gesture tracking and voice control) in the AR application. A Universal Windows Platform (UWP) application is developed with Mixed Reality Toolkit (MRTK) from Microsoft on the Unity 3D platform while Vuforia SDK from PTC enables marker detection and tracking. CAD file of the product (e.g., obj, fbx, stl) is used as a marker for the virtual environment so that no extra markers are required on the working station. The NDI coordinate system with respect to the global marker is transformed to the coordinate system with reference to the product marker and the AR content is displayed accordingly.

USE CASE APPLICATION

Assembly of Safety-Critical Components of Seating Systems

The use case for this study focuses on the monitoring and validation of manual assembly processes of airbag and seat pre-tensioning systems, which are safety-critical components for car seat products. The replica of a manual station is set up in the Automation Systems Group's Digital Automation Laboratory at WMG, University of Warwick, and comprises a section of conveyor, the articulated pallet (tilt and rotation) on which the product (i.e., seat frame) is mounted. The station also includes two power tools and tool mounts from which the operator picks the tool when a cycle starts, a bar code reader for product identification, and a touch-screen HMI.

One cycle of the assembly process in this use case includes tightening two bolts on the front of the seat's lower part, and two on the side of the backrest. The pose of the tool is continuously acquired by the NDI sensor. The data processing software then evaluates the pose of the power tool and validates whether the operation is completed by comparing it with the expected pose behaviour.

The screen-based work instructions software (see Figure 4) then provides instant feedback to the operator on the validation result and guidance to the next bolt position on both 2D and 3D visuals of the seat frame.

Figure 4: Screen-based work instructions with 3D model view (left) and overview of the DAMPO station set-up (right).

Integration of AR Application to Screen-based Tool Tracking System

To provide operators with a seamless in-process experience, AR features are integrated in addition to the screen-based instruction software to maximise the benefits of the system. HoloLens application is deployed in this use case application to provide the operator with a hands-free experience during the assembly process (see Figure 5).

To activate the AR content, the seat frame is used as a reference object maker for the HoloLens application. After detecting the seat frame and registering the virtual space to its pose using the camera on HoloLens, coordinate transformation from the optical tracker system to the virtual space is performed. Work instructions are then overlayed through the HMD on the seat frame. With continuous tracking of the seat frame, positions of work instructions are updated constantly to align with any movement of the seat frame.

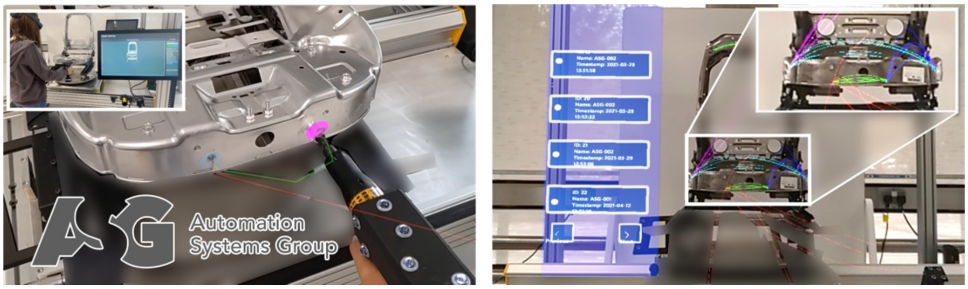

Figure 5: Left: HoloLens view of the second assembly process step, with the target tooltip position displayed as a magenta disc in the AR layer. Right: AR HoloLens view of tool paths for 6 cycles (historical data display).

The HoloLens, in the meantime, subscribes to the MQTT broker to receive real-time tool pose and validation results generated by the data processing software and update the guidance accordingly (i.e., changing the colour of the working instructions). Figure 8 shows the scenario that the first screwing is completed (in blue) and the next screwing position (in magenta). With the 3D pose of the tool position, the tool path of the operation is also visualised. In addition, historical tool paths can be displayed to provide traceability of previous processes.

CONCLUSION AND FUTURE WORK

The research demonstrates the implementation of a production-ready that combines process monitoring (via the tracking of tools) and user guidance systems. In-production deployment in the car seat and engine assembly plants has highlighted the need for further development, in particular, to tackle the occlusion of markers (multiple sensors), the integration with tool control systems to allow operation in the correct pose only, and with manufacturing execution systems (MES), to retrieve working locations associated with a specific product type. The use of HMD hardware and AR interfaces for guiding operators in production has proven to be unrealistic, mainly due to the limitation of the hardware (short battery life, fragile, disorientating over extended periods of use). However, initial testing has shown that the use of HMD AR can reduce operator training time for complex sequences of operations. Further research is required to quantify the cross-over point between task complexity and training time.

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