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This is a paper presented at Proc. 20th IEEE East-West Design and Test Symposium EWDTS 2024, Yerevan, Armenia, 13-17 Nov. 2024, pp. 1-5.

The published version is available at: https://ieeexplore.ieee.org/document/10873773

Recommended citation:

Heinrich, P., Akinsolu, M.O., Monir, S. and Vagapov, Y. (2024), 'Automatic deburring of 3D-printed parts using a delta robot and augmented reality'. In: Proc. 20th IEEE East-West Design and Test Symposium EWDTS 2024, Yerevan, Armenia, 13-17 Nov. 2024, pp. 1-5. doi: 10.1109/EWDTS63723.2024.10873773

Automatic Deburring of 3D-Printed Parts Using a Delta Robot and Augmented Reality

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***Abstract*—The strong demand for automated processes in modern manufacturing is driven by the need to replace manual and experience-based methods with emerging digital technologies to improve efficiency and performance. In mechanical engineering design, rapidly prototyped or 3D-printed parts are typically produced with excess material to ensure better print quality, necessitating a deburring step in the production process. While traditional deburring can be performed manually with tools, automating this process offers significant efficiency gains. This paper presents the automation of an application-specific deburring process through the integration of robotics, 3D-printing, and augmented reality systems. The programmed automatic deburring system deburred more than 100 3D-printed unmanned aerial vehicle parts (drone arms) under various settings to test and validate its performance. The results identified the optimal parameters as a robot speed of 43 mm/s, a grinder speed of 2,550 RPM, a grinder height of 78.5 mm, and a grinding tool diameter of 7.6 mm. The successful combination of robotics, 3D-printing, and augmented reality in this work strongly supports the Industry 4.0 paradigm, where industrial processes are expected to be more intelligent and collaborative, enhancing the interaction between machine tools and operators.**

***Keywords*—3D-printing, augmented reality, deburring, rapid prototyping, robotics, unmanned aerial vehicle**

I. INTRODUCTION

With the advent of Industry 4.0 (I4.0), many factories are becoming smart due to automation, decentralisation, digitisation, and intellectualisation of shop floor entities (that is, industrial machine tools and equipment) [1]. In this way, manufacturing processes and production activities are now able to respond promptly and directly to customer demands, allowing customisation and customer-centric production [1]. This trend has also reduced time-to-market (TTM) and increased the production throughput of tailored or customer-specific products (CSPs) [2]. Although many factors can be attributed to this improved level of efficiency in terms of reduced TTMs and increased CSPs, it has been mainly driven by emerging and present-day manufacturing technologies such as three-dimensional (3D) printing with rapid prototyping [3],[4], which is often assisted by vision systems such as augmented reality (AR) systems [5].

Various types of 3D-printing are purpose-built for rapid manufacturing processes, particularly the fabrication or prototyping of parts [6]. For example, stereolithography, which can be used for rapid prototyping and several other applications, and selective laser sintering, which is ideal for functional prototyping [6],[7]. Another popular type of 3D-printing is fused decomposition modelling, which is ideal for simple prototyping and proof-of-concept (PoC) modelling [6],[7]. Although these various types of 3D-printing machines offer reliably high degrees of accuracy, they are often designed to print excess material according to certain thresholds or tolerances [8]. As a result, very often 3D-printed parts need to be deburred to ensure that they are fit for installation and their intended applications.

Automating deburring via robots is changing and improving various sectors of the manufacturing industry as reported in [9]. In general, automation orchestrated by robots expedites manufacturing processes (including deburring), leading to significant changes in the manufacturing landscape in recent times. For example, according to the Boston Consulting Group, savings of up to 40% can be achieved by combining advanced robotics with other technologies, process improvements, and structural layout modifications on conversion costs [10]. In China, manufacturing labour costs have also been reduced by 18% with the adoption of robots [11]. These advantages derived from the adoption of robots to accelerate and automate processes in the manufacturing industry have been further amplified by the introduction of digital technologies such as augmented reality (AR) [5]. When used in conjunction with industrial robots, AR is mainly used for the control, design, training, and maintenance of robotic systems [12]. For example, Boeing used AR in the manufacturing programme and concluded that an increase in productivity was achieved by 40%, while simultaneously the wiring time was reduced by 30% without significant errors [13]. This example and several others in the manufacturing industry lend credence to the improved efficiency and robustness that the synergy of robotic systems and AR technologies can offer [14]. More specifically, robotic control combined with AR has been shown to improve the efficiency and robustness of manufacturing processes [14].

As the threshold for accuracy and precision in manufacturing processes such as the deburring of 3D-printed parts (unmanned aerial vehicle (UAV) components or parts) increases, and to minimise the overall TTM (e.g., to have tailored or customer-specific products), the use of robots in combination with AR to automatically and efficiently deburr 3D-printed parts becomes the go-to alternative. This paper presents the automation of the deburring of a 3D-printed UAV part with highly minimal human interaction or intervention which is based on the collaborative work between Schneider Electric and Switzerland Innovation Park to showcase a PoC for I4.0. The PoC in this paper demonstrates for the first time the conjunctive use of a delta robot and visualisation of machine operation data via AR to have an automatic deburring system (ADS) for customised, purpose-built 3D-

979-8-3315-1576-8/24 /$31.00

printed UAV parts (drone arms). Specifically, the main contributions of this paper are summarised as follows:

- PoC for the convergence of technologies (i.e. robotics and AR) to have an I4.0 paradigm, which expedites the automation of the deburring of 3D-printed parts.
- Experimental validation of an industrial communication protocol that improves the stability of the connectivity between machine tools and pieces of equipment on the shop or manufacturing floor for the automation of the deburring of 3D-printed parts.
- Enhanced visualisation of dynamic data from machine tool and equipment operations via AR to support robust system operations and pre-emptive maintenance tasks.

The remainder of this research work is organised as follows: Section II discusses related works with a focus on robotic systems and AR technologies, Section III details the programming and implementation of the ADS, and Section IV provides further discussion including experimental tests and results. Concluding remarks are provided in Section V.

II. RELATED WORKS

The history of robotics goes back to the third century (250 BC) [15]. However, the principles which constitute the basis of practical robots, that is cybernetics, were not postulated until the late 1940s [16]. A large variety of robots have been designed and developed for various applications. Of particular interest is the parallel robot, also called a parallel manipulator, which is widely used in manufacturing to automate work packages [17]. The delta robot is a type of parallel robot; one of its key design characteristics is its ability to maintain its orientation when it is operational [17]. Various designs of the delta robot with several control schemes have been investigated to demonstrate the wide range of industrial applications [17]. The iterative matrix relations and other scientific and mathematical relations for the geometric, kinematic, and dynamic analysis of the delta parallel robot are also well-established [18]-[20]. Therefore, the delta robot is quite a popular choice for industrial process automation such as pick and place operations that are required for the automation of deburring [21],[22].

Nowadays, it has been demonstrated that it is possible to enhance the reliability and robustness of industrial robots using emerging and digital technologies such as AR [14]. For example, maintenance services are often implemented for contemporary industrial robots using AR [23]. AR, as a digital technology, is based on the integration (or overlay) of virtual 3D objects with their real-world counterparts in real-time to derive more insight or perceptual information from the objects [14],[23],[24]. Although several real-world case studies have demonstrated the feasibility of AR for many practical applications (including industrial applications) [25]-[27], there seem to be very limited studies focusing on the deburring of 3D-printed parts through the conjunctive use of delta robots and AR technologies. This could be because there are still some challenges in the design, development, and commercialisation of industry-standard hybridised robotic and AR applications [28]-[31]. Some of these challenges include (but are not limited) to flexibility and optimum exploration of augmented space, and feature selection and classification for object recognition and identification [26],[28]-[30]. To overcome some of these challenges, genetic programming is often employed to evolve the behaviour of robots to make them more robust to varying control paradigms and fit for purpose in industrial applications [32].

TABLE I. OVERVIEW OF THE ADS SHOWING THE COMPONENTS AND THEIR FUNCTIONS.

Component	Feature/Function	Dimension/ Quantification
Deburring Chamber	Deburring of small and large parts (i.e. drone arms). Loading and unloading of parts (i.e. drone arms). Houses the robot (i.e. the delta robot)	1000 mm × 1000 mm × 100 mm
Programmable Logic Controller (PLC)	Controls the deburring machine and the delta robot. High reliability. Provides data for AR platform.	Downtime of less than 1% per year.
AR Platform	Tool for maintenance. Projects data on the deburring machine in real-time. Works with different handheld devices.	Lag less than 30 s. Supports multiple operating systems.
Communication	Transports data across the deburring machine. Provides process data to the AR platform. Secures data transmission.	Username and pass-word protected.

In this work, genetic programming is employed for the ease of integration of a delta robot and AR for industrial applications, allowing the exploration of the flexibility of the delta robot for optimal pick-and-place operations to make a unique case for the automatic deburring of a 3D-printed parts. To the best knowledge of the authors, this specific case of conjunctive operation of a delta robot and AR for the automatic deburring of 3D-printed UAV parts is reported for the first time in this work.

III. SYSTEM OVERVIEW AND SYSTEM SETUP

A. System Overview

Table 1 shows that the main components for the implementation of the ADS are the deburring chamber featuring the deburring machine and the pick-and-place operations of a delta robot, a programmable logic controller (PLC) for controlling the delta robot, an AR platform, and data communication between these components. Additional details (including features or functions, dimension, and quantification) of these components are provided in Table I. For the ADS, the specific robotic system employed is the Schneider Electric Delta Robot (Lexium P0) mainly due to its fast-paced pick-and-place operations, extremely wide field reach, high level of precision and lightweight [33]. However, it should be noted that Yamaha SCARA Robot (YK600XGL) [34], and Fanuc articulated robot (CR4ia) [35], can also be used for the same purposes.

The AR platform used for ADS comprises tag recognition and superimposed AR implemented using Schneider Electrics “EcoStruxure Augmented Operator Advisor” mainly due to its ease of programming and added features [36]. An alternative platform that may perform similar functions with fewer features is the “Vuforia Augmented Reality SDK” [37]. The PLC selected for ADS is Schneider Electric LMC106 [38], which offers the largest

Fig. 1. The setup of the ADS on the shop floor.

random access memory (RAM), the fastest cycle time and a framework that is relatively self-explaining and well documented compared to alternatives such as Siemens D435 SIPLUS [39] and ABB MicroFlex e190 [409]. Additionally, the Schneider Electric LMC106 supports a very wide range of required communication protocols that can adequately support an extension of the operations of the ADS.

Some of the machine-to-machine (m2m) communication options available for deployment on the ADS include message queueing telemetry transport (MQTT) and OPC foundation unified architecture (OPC UA). OPC UA was adopted for the ADS due to its excellent security without compromising on the data volume, communication speed and overall reliability. It should be noted that the AR feature of the ADS requires a large data volume, as all process variables have to be updated simultaneously and as fast as possible, creating a massive data block to be sent at once. OPC UA communications can efficiently handle such volumes of data [41].

TABLE II. PSEUDOCODE FOR THE ESSENTIAL OPERATIONS OF THE ADS.

```
#######################
While System is Ready Do
#######################
    If
        Big Arm Ready to Pick = True Then
        Move in Front of Big Arm Pick Position
        Move over Pick Position And Parse the Big Arm Gcode
        Turn on Vacuum And Pick the UAV Part
        Move in Front of the pick position
        Move over grinder
        Retract the loading cylinder
    Else If
        Small Arm ready to Pick = True Then
        Move in Front of Small Arm Pick Position
        Move over Pick Position And Parse the Small Arm Gcode
        Turn on Vacuum And Pick the UAV Part
        Move in Front of the Pick Position
        Move over Grinder And Retract the Loading Cylinder
    End If
#######################
    Start Grinder #After Partt has Successfully been picked
    Run Parsed Gcode
    Advance unloading cylinder
    If
        Small Arm Dcburred = True Then
        Move Over Small Arm Place Position
        Place UAV Part on Small Arm Place Position
    Else If
        Big Arm Deburred = True Then
        Move Over Big Arm Place position
        Place UAV Part on Big Arm Place Position
    End If
#######################
Move To Wait Position
End While
#######################
```

TABLE III. OPTIMUM PARAMETRIC VALUES FOR THE ADS: SET 1 (MOST OPTIMAL) TO SET 5 (LEAST OPTIMAL).

Set	**Speed of the Robot**	**Speed of the Grinder**	**Height of the Grinder**	**Diameter of the Grinding Tool**
(1)	43 mm/s	2,550 RPM	78.5 mm	7.6 mm
(2)	45 mm/s	2,700 RPM	78.5 mm	8.0 mm
(3)	50 mm/s	2,800 RPM	79.0 mm	7.8 mm
(4)	66 mm/s	3,000 RPM	79.0 mm	7.6 mm
(5)	100 mm/s	3,000 RPM	79.0 mm	7.6 mm

B. System Setup

By splitting the ADS into individual subsystems, namely, the deburring chamber (housing the parallel delta robot), the AR platform, the PLC and communication (see Table I), the solution-finding process has been split up into the same categories to aid decision-making. As all subsystems are evaluated individually, the complete ADS will consist of the combined evaluated subsystems that are best suited to the deburring task. This resulting overall system setup is shown in Fig. 1. It should be emphasised that the ADS requires a robot with at least four axes and a multi-axis logic controller. So, the task of picking, deburring and placing the UAV parts (i.e., drone arms) is assigned to the parallel delta robot via a vacuum gripper, a fixed rotary grinder, and a pneumatic delivery system. The Schneider Electric LMC106 previously described controls the robotic system, communicating over OPC UA. The AR platform (EcoStruxure Augmented Operator Advisor, described earlier) is then configured to provide maintenance and oversight tasks for the ADS by implementing an AR-based tag identification and recognition system using a human-machine interface (HMI). The overall pseudocode for the essential operations of the ADS is listed in Table II.

IV. RESULTS AND DISCUSSION

A. Automatic Deburring

To determine the optimal parameters of the ADS (see Table II), more than 100 deburring cycles were conducted, each with different individual settings. After each cycle, the 3D-printed part (that is, the drone arm) was inspected and one parameter was adjusted at a time. This systematic approach resulted in a favourable combination of robot speed and grinder velocity. The five most effective parameters are listed in Table III. The results of the deburring were individually compared to the control—a drone arm that had not been deburred—and previously deburred drone arms to assess the impact of parameter changes on the quality of the deburred part. The set of metrics that provided the best deburring results are reported in Table III in decreasing order of optimality, indicating that the parameters in the combination reported as in set (1) produced the best overall results.

Upon close inspection of the deburred part from set (1), shown in Fig. 2, it was observed that the burr was cut off at approximately a 45° angle. However, the cut surface appeared uneven due to vibration in the gripper, which could not be eliminated by adjusting the parameters alone. Consequently, it is necessary to implement mechanical modifications and upgrades to the gripper to reduce

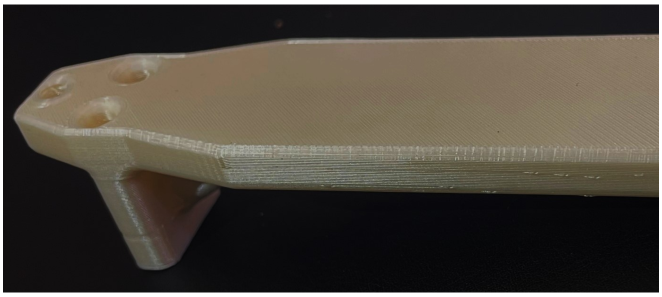


Fig. 2. The most optimal deburred part.

vibration and thus enhance the overall quality of the deburred part.

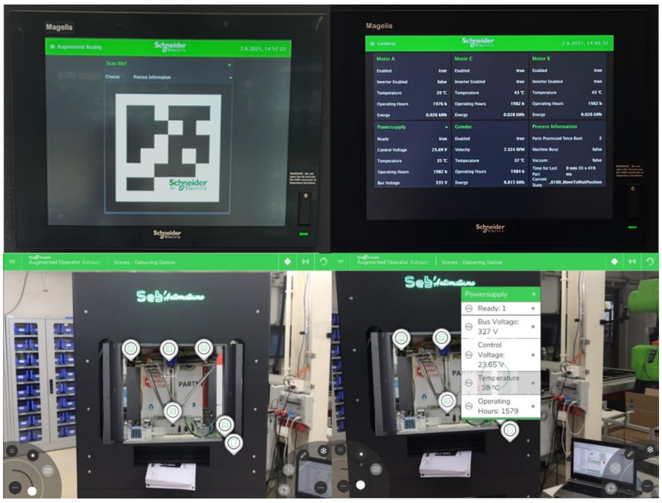
B. AR Application or Platform

As the AR application is intended for maintenance and oversight purposes, the visualised data have been determined to focus on machine safety and process variables. To ensure that the AR application is as user-friendly as possible, AR tags are displayed in the HMI using the Node-Red dashboard [30], and a dropdown menu, as shown in Fig. 3. Since AR variables are processed through Node-Red, it is logical to display these same variables on the HMI within the Node-Red dashboard. The pool of available variables is defined by the machine's components, as only the data provided by these components can be obtained. However, process information variables can be calculated during operations. The variables relevant to oversight and maintenance tasks are divided into two categories: hardware information and process information.

Hardware information includes temperature, energy consumption, and operating hours of the delta drives and grinder. Additionally, the DC bus voltage and the supply voltage of the mains power supply are visualised. The process information includes the number of parts that had been deburred in the past 24 hours, the time taken to deburr the last part, the current state of the program, the general state of the machine and the state of the vacuum. Therefore, with the AR, program failures could be identified and advanced process oversight was also ensured. Moreover, with the AR platform, the debugging of the state of the robot through a display of its state machine's status was also made possible. As shown in Fig. 3, the AR application projects an image of the internal workings of the machine onto the housing. Depending on the AR-tag, relevant information is displayed at points of interest. When the cursor in the centre of the screen moves over these points of interest, the information is revealed, as shown in Fig. 3.

V. CONCLUSION

This study focuses on the investigation, design, and development of an automatic deburring system (ADS) that leverages the synergy of robotics, 3D-printing, and augmented reality (AR) technologies. The integration of these technologies to realise the ADS exemplifies an Industry 4.0 paradigm. Specifically, the ADS employs a Delta robot to pick, deburr, and place 3D-printed parts (in this case, drone arms) using a vacuum gripper. Additionally, the ADS includes a fixed rotary grinder and a pneumatic delivery system to support these operations. The ADS specifications are as follows: a Schneider Electric LMC 106 for control, OPC UA for communication, and Schneider Electric's Ecostruxe AR System, which uses AR tags to facilitate maintenance and oversight tasks. The ADS was tested by deburring more than 100 3D-printed mechanical parts (drone arms) with various settings. Thorough evaluations determined that the optimal parameters for the ADS are a robot speed of 43 mm/s, a grinder speed of 2,550 RPM, a grinder height of 78.5 mm, and a grinding tool diameter of 7.6 mm.



2.6.2021, 14:57:22

Choose Process Information

2.6.2021, 14:46:32

Motor A
Enabled true
Inverter Enabled false
Temperature: 29 °C
Operating Hours 1976 h
Energy 0.026 kWh

Motor C
Enabled true
Inverter Enabled true
Temperature 43 °C
Operating Hours 1982 h
Energy 0.028 kWh

Motor B
Enabled true
Inverter Enabled true
Temperature 43 °C
Operating Hours 1982 h
Energy 0.026 kWh

Powersupply
Ready true
Control Voltage 23.69 V
Temperature 35 °C
Operating Hours 1982 h
Bus Voltage 335 V

Grinder
Enabled true
Velocity 7.324 RPM
Temperature 37 °C
Operating Hours 1984 h
Energy 9.815 kWh

Process Information
Parts Processed Since Boot: 2
Machine Busy: false
Vacuum : false
Time for Last Part 0 min 33 s 419 ms
Current State: _0100_MoveToWaitPosition

Powersupply
Ready: 1
Bus Voltage: 327 V
Control Voltage: 23.65 V
Temperature : 38 °C
Operating Hours: 1579

Fig. 3. AR application.

ACKNOWLEDGEMENT

The authors would like to thank Schneider Electric (Schweiz) AG and Switzerland Innovation Park for supporting the work carried out in this paper.

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