A digital twin-driven ultra-precision machining system

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Abstract. The demand for ultra-precision machining has expanded significantly across industries such as aerospace, automotive, electronics, and medical sectors. These industries require parts manufactured to micrometre tolerances in a timely and cost-effective manner. To address these demands, efforts have been focused on developing digital twin technology for ultra-precision machining, aimed at improving production accuracy and efficiency. One of the primary challenges in ultra-precision machining is time-consuming setup due to manual workpiece handling. Additionally, machining speeds are limited to mitigate dynamic errors, further prolonging production times. This paper proposes a digital twin system designed to automate workpiece handling and correct dynamic errors in real time to tackle these challenges. The proposed digital twin comprises two systems: one for controlling a collaborative robot arm (COBOT) to automate workpiece handling with corrective action, eliminating the need for manual loading and unloading; and another for controlling a hybrid mill to mitigate dynamic errors through real-time machine learning-based prediction of elastic deformation allowing for higher machining speeds. In this paper, the current progress is discussed, and a methodology for validating this digital twin system is proposed. The proposed validation process will involve machining microfluidic devices using the digital twin system, compared to conventional machining methods to assess the effectiveness.

1 Introduction

Ultra-precision machining processes are utilised by various industries like aerospace, automotive, electronics, and medical sectors to fabricate intricate components with extreme precision and accuracy. However, despite its significance, the accuracy-efficiency trade-off is still a critical challenge in ultra-precision machining. One of the chief reasons for the lack of efficiency is the involvement of manual work handling methods which leads to additional time and costs. There exists a need for a transformative solution which can improve the accuracy together with automating the work handling.

Digital twin technology is rapidly emerging as a powerful solution for addressing complex manufacturing challenges. Initially proposed for product life cycle management by Grieves[1], the concept of digital twins has evolved significantly over the past decade. A current and accurate definition of digital twins can be attributed to the Advanced Manufacturing Research Centre (AMRC)[2]: "A live digital coupling of the state of a physical asset or process to a virtual representation with a functional output."

The utilisation of digital twin technology for enhancing production quality, throughput, and complexity has been a common subject of investigation by researchers, as evidenced by the extensive body of research in this domain. For instance, the application of digital twins to optimise product assembly processes has garnered considerable attention. In [3], a theoretical framework is proposed for a digital twin-driven automated assembly system tailored for high-precision products, with the overarching goal of enhancing assembly efficiency and ensuring consistency in product quality. Moreover, numerous digital twin implementations have demonstrated their efficiency in improving machining performance by optimising workpiece handling. Notably, [4] presents a digital twin capable of predicting disturbances in workpiece movement along a conveyor system, thereby enhancing performance and cost-effectiveness in workpiece handling operations. Similarly, [5] introduces a digital twin designed to monitor machining parameters for thin-walled structures, leveraging dynamic characteristics for improved machining precision. Additionally, [6] employs image processing techniques to facilitate automated pick-and-place operations by identifying product orientations, thereby reducing manual workload through automated gripping point identification. Digital twins have also been instrumental in enhancing the control of CNC machines for automated manufacturing. For instance, [7] describes the development of a

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digital twin tailored for hybrid manufacturing processes combining metal additive manufacturing and CNC machining. This system enables precise identification of printed part locations, code orientation, and real-time monitoring for machining chatter.

Furthermore, digital twins have revolutionised production control systems by enhancing data collection, production efficiency, and error detection capabilities. Noteworthy examples include [8], which presents a comprehensive digital twin framework for workshop-scale production encompassing process, operation, and IoT/sensor levels. Although automated production is facilitated, real-time corrective actions are not feasible during production. Similarly, [9] introduces a digital twin-driven manufacturing cyber-physical system, enabling parallel control of smart machinery for mass customisation of products. Additionally, [10] proposes a scheduling digital twin capable of dynamically adjusting job lists based on deviations and system influences. Moreover, [11] outlines a digital twin framework for digitising smart manufacturing environments, incorporating a tri-model approach comprising digital, computational, and graph-based models.

The examples underscore the transformative potential of digital twins in manufacturing, offering enhanced accuracy, efficiency, and reliability. To contribute to the ongoing development of digital twin technology in manufacturing, this paper will present an experimental approach aimed at improving the production accuracy and efficiency of ultra-precision parts using a hybrid mill and Collaborative Robot (COBOT). The proposed digital twin system is aimed at facilitating the automated handling of workpieces and the real-time implementation of corrective measures. The proposed digital twin comprises two distinct components: one dedicated to workpiece handling and another focused on a hybrid mill. The workpiece handling digital twin enables the automated loading and unloading of workpieces onto a hybrid mill through the utilisation of a COBOT. This system incorporates a digital tracking system to monitor the spatial coordinates of the COBOT and ensures precise placement of the workpiece. Real-time corrective measures are implemented to adjust the position of the COBOT and optimise workpiece placement. Concurrently, the hybrid mill digital twin is designed to gather and store relevant data during the machining process. This collected data serves as the basis for implementing real-time corrective actions, primarily directed towards encoder value correction.

Section 2 will explain the proposed system architecture and the connection between digital twins, while Section 3 will provide the methodology for validating the digital twin models. Finally, Section 4 will summarise the conclusion and findings of this research endeavour.

2 Integrated digital twin approach

The integrated digital twin will have the capability to predict and correct dynamic errors that occur during the machining process or when handling workpieces. According to Zhao et al.[12] dynamic error is the “deviation of the actual displacement at the effector end of axis relative to the reference (setpoints) displacement in the feed motion”. The nature of dynamic error depends on the point of measurement: errors within the servo loop are referred to as tracking errors, while errors outside the servo loop are attributed to elastic deformation or vibration [12]. In this paper, the focus will be on addressing elastic deformation, commonly known as "jerk"[13]. The challenge with measuring jerk lies in the fact that elastic deformation cannot be directly measured with encoders, as the deformation of the structure does not result in movement on the axis. Traditionally, reducing jerk involves decreasing the feed rate of the machine to mitigate the forces generated during acceleration and deceleration. However, this approach limits the speed at which parts can be produced, thereby increasing the cost of manufacturing ultra-precision parts. A more effective solution would enable machines to maintain high speeds while ensuring accuracy and providing a method for rapid and accurate placement of material into machines. This approach would not only enhance production efficiency but also reduce costs associated with ultra-precision part manufacturing.

The primary objective of this digital twin system is to achieve micron-level corrections in real-time for the positioning of the COBOT and Hybrid Mill, automate the handling of workpieces for seamless loading and unloading, and enhance production speed by mitigating dynamic motion errors. Achieving these objectives holds the potential to reduce production time for ultra-precision parts, thereby expanding their utilisation across industries such as aerospace, automotive, electronics, and medical. This proposed digital twin will accurately predict and correct the dynamic motion errors inherent in the machining process due to jerk. To address this limitation, machine learning models are trained using acceleration values obtained from the machine. These models employ explainable machine learning techniques to derive equations capable of accurately predicting machine dynamic motion errors. Through these techniques, the machine learning algorithms identify the minimal key features necessary to predict the dynamic motion error of each machine. The key features are used to predict the dynamic motion error effectively reducing computational demand for predictions. This process ensures transparency and interpretability in the predictive modelling, facilitating a deeper understanding of the underlying mechanisms driving machine behaviour. Notably, the equations and key features employed differ between the COBOT and Hybrid Mill digital twins due to their distinct dynamic characteristics.

2.1.1 COBOT Digital Twin Design

The digital twin of the COBOT encompasses several key features aimed at enhancing its operational capabilities within the manufacturing environment. These features include automated corrective action, automated control for workpiece handling and position tracking. Notably, the automated corrective action functionality enables precise placement of workpieces within the mill, thereby facilitating accurate machining processes. Furthermore, position tracking capabilities are leveraged to ensure correct HYBRID origin point calibration without the need for manual measurements or adjustments, minimising errors in positioning. The integration of the COBOT digital twin with the Hybrid Mill digital twin streamlines data exchange and control processes, facilitating the coordinated operation of both systems.

Previous research efforts have explored and documented the capabilities of the COBOT digital twin. For instance, Walker et al. [14] highlighted the tracking capabilities and fundamental design concepts of the digital twin. Additionally, Abhilash et al. [15] have successfully implemented machine learning methodologies for dynamic error prediction and subsequent corrective action. In these previuse papers the operation of the COBOT digital twin revolves around the collection of acceleration values near the end effector to predict dynamic motion errors. Upon prediction of dynamic motion corrections, adjustments are applied to the COBOT's target locations, ensuring precise positioning for subsequent actions. The effectiveness of this digital twin system was assessed through testing using a ball bar. Initially, testing was conducted solely in the XY axis. In these iterations, the corrective action process implemented by the COBOT digital twin successfully reduced the mean dynamic motion error in the XY plane by an average of 7.27 micrometres over a movement distance of 408.105 millimetres. Subsequent improvements to the systems and testing conditions enabled testing to be conducted in XYZ by travelling at a fixed radius around a point. In the latest version, testing of the digital twin in XYZ resulted in a mean error reduction of 299.8 micrometres over a movement distance of 3485.264 millimetres.

2.1.2 Hybrid mill digital twin design

The digital twin dedicated to the Hybrid Mill encompasses several key features aimed at enhancing its functionality within the manufacturing environment. These features include automated corrective action, comprehensive data collection for tracking and optimisation purposes, real-time digital display of mill operations, and seamless integration with the COBOT. The automated corrective action functionality enables real-time correction of predicted errors during machining processes, ensuring precision and accuracy. Moreover, the collected data facilitates continuous tracking of errors and optimisation of mill performance, enabling efficient operation. The real-time digital display feature provides a visual representation of mill operations.

The operation of the Hybrid Mill digital twin follows a similar design to the COBOT, wherein dynamic motion errors are predicted using acceleration data. However, due to the separate axes of movement, two accelerometers are utilised (one for the XY axis and another for the Z axis). Machine learning techniques are employed to generate equations for error prediction, with training data provided by conducting ball-bar experiments. The corrective action mechanism of the Hybrid Mill involves applying offsets to encoder values in real time, enabling micron-level adjustments during machining. This adjustment is achieved by setting the encoder step per voltage on an analogue input of the controller. When a voltage is measured, the controller applies an offset to the encoder values based on the configured parameters. This process enables micron-level adjustments using a microcontroller and a Pulse-width modulation (PWM) to the voltage module, as depicted in Figure 1.

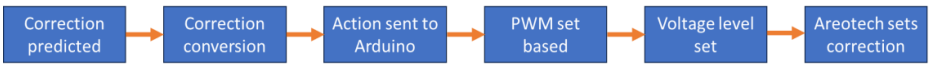

Fig. 1. Hybrid mill encoder corrective action

Using this method equations have been created for the hybrid mill to predict the dynamic motion error. The effectiveness of the equations is yet to be tested but theoretical models have shown a reduction in dynamic motion error. Examples of these equations for X forward motion as shown in equation (1) which has a prediction accuracy value of 84.3%and X backwards motion in equation (2) which has a prediction accuracy of 84.8%.

$$0.274 - 0.532e^{-\frac{1.11(0.377-F8)^2}{(0.000494\,F21-1)^2}-13.5(0.0924\,F5-1)^2} \quad (1)$$

$$-0.351 + 0.727e^{-2e^{-13900(1-0.000469\,F21)^2(0.75\,F4-1)^2-75.9(F8-0.0303)^2}} \quad (2)$$

2.2 Combined digital twin

The proposed digital twin system comprises two interconnected components: one dedicated to workpiece handling with the COBOT and another tailored for the hybrid mill. The comprehensive architecture of the digital twin is illustrated in Figure 2, depicting the interconnection of accelerometers with both the Hybrid Mill and COBOT, as

well as the flow of data between each module with Figure 3 depicting a flow chart of the combined digital twin operation.

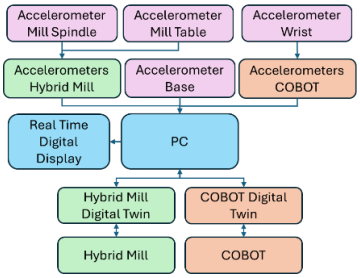

Fig. 2. Architecture of digital twin

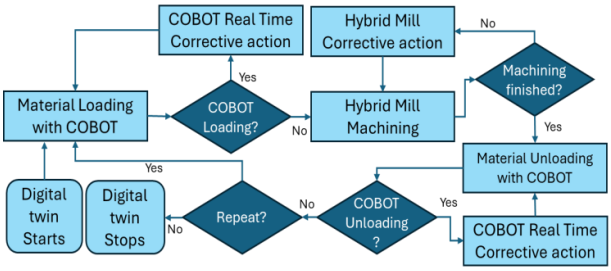

Fig. 3. Digital twin system flow chart

The workpiece handling subsystem operates through the use of a COBOT, facilitating automated loading and unloading processes. This subsystem ensures seamless coordination between the COBOT's movements and the positioning of workpieces within the machining environment. Concurrently, the hybrid mill subsystem is responsible for monitoring and optimising machining operations in real-time.

The entire system relies on four accelerometers for its operation: two dedicated to the Hybrid Mill (one on the table for XY and one on the spindle for Z), one for the COBOT wrist, and one connected to the mill base to monitor ground vibrations. To optimise computational resources, the two digital twins operate independently and not simultaneously.

The flow chart in Figure 3 begins with the digital twin starting, the COBOT will commence loading suitable material into the Hybrid Mill using its electromagnetic end effector. Simultaneously, corrective action and tracking will be implemented to monitor and optimise the placement of the workpiece. Once loading is complete, the workpiece's location will be transmitted to the Aerotech software, resetting the origin point and initiating the machining process. Throughout the machining operation, corrective action and data collection will be ongoing. Upon completion of the machining process, the COBOT will proceed with unloading the material based on the location of the Hybrid Mill table. Concurrently, corrective action and monitoring will be carried out to ensure the smooth and precise unloading of the workpiece. Once unloading is finished, the system will assess whether the process needs to be repeated. If necessary, the system will restart both the COBOT and Hybrid Mill. Otherwise, the digital twin will halt both systems.

3 Case study

To validate the effectiveness of the proposed digital twin system, an experiment must be conducted to assess the performance of the COBOT, Hybrid Mill, and Control Digital Twin simultaneously. This experiment should demonstrate improvements in machining accuracy, production speed, and repeatability.

Below is an overview of the equipment utilised in this study: a UR10e COBOT equipped with a custom electromagnetic end effector for workpiece handling, and a custom-built Hybrid Mill incorporating an Aerotech A3200 CNC controller. Acceleration data is captured using PCB model 356B18 tri-axial accelerometers, with data collection facilitated by a National Instruments cDAQ-9174 system alongside NI-9234 models. The software ecosystem comprises Aerotech's Automation 3200 software for Hybrid Mill operation, RoboDK for COBOT operations, and MATLAB for digital twin modelling, data communication, and comprehensive system control.

The selected part for machining validation will be a microfluidic device fabricated from stainless-steel plates. Microfluidic devices are chosen due to their stringent requirements for precision and repeatability in fluid dynamics applications. Stainless steel is selected as the material of choice for its durability, chemical inertness, and suitability for high-temperature chemical applications, particularly in drug screening and analysis [16-18].

Utilising stainless steel enables automated manufacturing of parts with high accuracy and flexibility in production design, tailored to specific testing requirements. The microfluidic device design chosen for experimentation is a 200 µm channel fluid resistor, as depicted in Figure 4. This design allows for focused testing and evaluation of the digital twin's capabilities without the complexity of a full-scale microfluidic device.

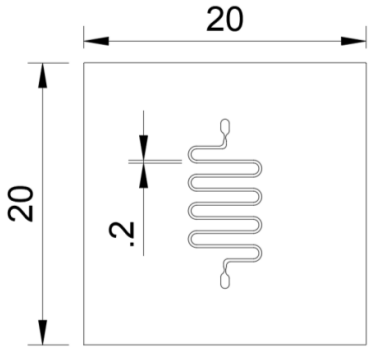

Fig. 1. Design of microfluid device

For the test, the component will be machined three times using both the digital twin system and a human operator. The digital twin will autonomously execute the machining process, loading, machining, and unloading of all three parts, with real-time corrective action implemented throughout. The human operator will prepare the machine for machining and replace the workpiece after each production run, ensuring the correct setup of the origin point with no changes to the machine settings. Once six parts have been manufactured (three using the digital twin system and three manually), they will be subjected to comparative analysis based on the three metrics. Machining accuracy will be assessed using an optical microscope to measure dimensional deviations of the microfluid device channel. Production time will be calculated as the total machining time for each set of parts. Repeatability will be evaluated by examining the consistency of machine placement and movement throughout the machining process. The proposed test seeks to assess the performance of the digital twin system in comparison to a human operator during the machining of a component. This evaluation will specifically examine three key metrics: accuracy, production speed, and repeatability. Based on preliminary findings and tests conducted, it is anticipated that the utilisation of the digital twin will lead to improvements in both accuracy and efficiency in ultra-precision manufacturing processes.

The experiments conducted thus far have shown an error reduction of the COBOT by 299.8 micrometres. Additionally, the equations developed for predicting dynamic motion errors in the hybrid mill have shown an accuracy prediction rate of over 84% for the X-axis. Given these promising outcomes, it is expected that the digital twin system will contribute to enhanced accuracy and efficiency in ultra-precision manufacturing processes. The proposed test will serve to further validate these expectations and provide insights into the system's performance compared to manual operation by a human operator.

4 Conclusion

This paper has conducted a comprehensive examination of a digital twin-driven ultra-precision manufacturing system, integrating a COBOT and a hybrid mill digital twin. The proposed approach not only enables automatic prediction and correction of dynamic errors in real time but also enhances system repeatability while providing insights into the machine's dynamic properties. These improvements could potentially pave the way for the development of systems capable of producing ultra-precision products with greater accuracy and efficiency.

The current results from the COBOT digital twin demonstrate a reduction in dynamic motion errors by 299.8 micrometres observed over a movement distance of 3485.264 millimetres. While the effectiveness of the Hybrid Mill digital twin is yet to be fully tested, initial findings are promising. It is currently able to predict dynamic motion errors in each axis for both forward and backward motions with over 84% accuracy. Further development of the digital twin will involve final testing to measure the extent to which dynamic motion errors can be reduced. The combined digital twin system has not been tested as a complete system yet, as it requires the full operation of the Hybrid Mill digital twin. Once this is achieved, the proposed experiment will be conducted to evaluate the effectiveness of the combined digital twin in improving the accuracy and efficiency of ultra-precision machining processes.

Recent research endeavours have highlighted the potential improvements to production systems through the utilisation of digital twins. This has motivated researchers to develop digital twins capable of enhancing efficiency in workpiece handling and improving accuracy. The proposed digital twin system has the potential to fulfil both objectives, thereby reducing production costs and expanding capabilities across various sectors such as aerospace, automotive, electronics, and medical industries for further research and development.

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