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Published in:
IEEE Access

Published: 01/01/2019

Document Version:
Final Published version, also known as Publisher's PDF, Publisher's Final version or Version of Record

Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1109/ACCESS.2019.2891060

Publication details:

Citing this paper
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Digital Twin-Driven Cyber-Physical System for Autonomously Controlling of Micro Punching System

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This work was supported in part by the National Natural Science Foundation of China under Grant 51605101, Grant 51705091, and Grant 51675108, in part by the Science and Technology Plan Project of Guangzhou under Grant 201804020092, in part by the Science and Technology Planning Project of Guangdong Province of China under Grant 2015B010128007, Grant 2016A010106006, and Grant 2017B090911012, in part by the Fundamental Research Funds for the Central Universities under Grant 2015ZZ079, in part by the Hong Kong Scholars Program under Grant XJ201817, in part by the Outstanding Young Professors Training Plan of Guangdong Province, and in part by the University Innovation and Entrepreneurship Education Major Project of Guangzhou under Grant 201709P05.

ABSTRACT Microstructure functional surface is widely used in an optical system because of its special micro-topological structure and particular physical properties. This paper presents a context-aware autonomously controlling method of micro-dots punching machine tool via establishing the digital twin-driven cyber-physical system. Key enabling techniques on twinning of cyberspace and physical equipment are discussed. A dynamic adjustment model of piezoelectric ceramics for micro-dots punching is presented based on the high-precision online detection and control system. A novel staggered punching approach is proposed for improving the punching speed. A joint optimization model is proposed for coordinating micro-punching system and staggered process. Context-aware autonomous adjusting of the system with errors analysis and compensations in the punching process is realized. Finally, a positioning accuracy of 2 μm and a high punching speed of 20–65 dots/s are achieved. This paper is expected to provide a new approach for incorporating smart-enabling techniques in the ultra-precision machining of microstructure arrays.

INDEX TERMS Digital twin, cyber-physical systems, micro punching system, online joint optimization, autonomously controlling.

I. INTRODUCTION

THE rapid upgrading of smart cellphone drives the improvement of the precision machining accuracy of machine tools. For instance, the machining of microstructure arrays in Light Guide Plate (LGP) of LCD from cellphone belongs to a kind of ultra-precision machining (Figure 1), and the massive micro-dots in LGP are usually machined by piezoelectric ceramics-based Micro Punching System (MPS).

A conventional way for high efficiency mass production of microstructure (e.g., micro-dots) functional surface is micro forming-based replication technique because of its process simplicity, high reusability, and excellent production capability. During the copy process of the microstructure array in functional surface, the machining quality of microstructure surface molds has decisive influence on the performance of final product. Among various micro forming processes (e.g., micro forging, micro coining, and micro sheet metal forming) [1], punching of massive micro-dots is still challenging due to the difficulty and complexity in covering accuracy requirements of microdots with random sparse lattice and non-equidistant nature. The common goal of MPS is to produce a uniform microdots quality with lower cost and minimum machining time in mass production paradigm. Therefore, the development of ultra-precision and high-speed MPS has great significance. Two key performance metrics in the punching process are the quality of microdots and punching speed.

Conventional research usually carried out the optimization and simulation of MPS before manufacturing process, while the key in developing an ultra-precision MPS is to build
an interoperability between the cyber space and physical space for online optimization. Cyber-Physical System (CPS) is emerged as the new generation of Internet-of-Things vision [2], via incorporating and reasoning about extracted knowledge hidden in manufacturing activities, with the goal of finally integrating the cyber and physical worlds [3]. It allows an efficient process quality prediction and controlling of the micro-dots punching without the need for time-expensive pre-production physical mock-ups or offline simulations. However, there are two challenges hindering the implementation, namely, the cyber-physical twining and the contextual-aware autonomously controlling of MPS. The first challenge origins from a difficulty in multi-source status data perception of dynamic environment [4]. The second challenge results from the need of timely smart decision-making in complex context [5].

To tackle above gaps, a digital twin (DT) model of MPS is proposed to perceive the context of the punching process and thus to form self-adaptive control actions catering to the physical environment. A manufacturing cognitive-loop is formed based on open architecture of numerical control system. Based on the cognitive-loop among cyber and physical system, an online joint optimization of punching system and process can be performed via characterizing both system and processes’ situations for adaptive coordinating in CPS. How the embedded systems of MPS will be leveraged to provide both context-aware and delay-tolerant control actions will be elaborated. Finally, a demonstrative MPS named GDUT is developed for verifying the feasibility of proposed approach.

The rest of this paper is organized as follows. After a literature review on the digital twin and control system in manufacturing in section II, section III presents an open architecture of digital twin-driven cyber-physical system for autonomously controlling of micro punching system. Aiming at preparing theoretically-grounded solutions for practical purposes, three key enabling techniques for implementing digital twin-driven CPS in micro punching system are analyzed in section IV. A prototype system is developed as a demonstrative application in section V. Finally, the discussions and conclusions are presented in Section VI and VII, respectively.

II. RELATED WORKS
Coordinating the control of all moving parts/actuators in MPS is important for achieving high speed and precision. The challenge is tougher with the random sparse lattice and non-equidistant nature of microdots. As the piezoelectric ceramics (i.e., PZT, actuator of punching process) has relatively complex non-linear electromechanical coupling relations and mechanisms, it is improper to construct the micro control model in a static mathematical manner (e.g., Preisach Model, Maxwell Model, Bouc-Wen Model, Polynomial Fitting Model, and Prandtl-Ishlinskii Model). Meanwhile, the conventional digital prototype approach is more like an off-line simulation of system before start of production, which lacks of real-time data to conduct a high-fidelity modeling and optimization.

With the rapid development of computer, microelectronics, and automatic control technologies, when dynamic digital models are used as the language for controlling machines, the precision machining can become faster, more flexible and more accurate. A potential solution is to build digital twin for supporting real-time synchronization of cyber and physical system [5]. Various data analytics can be integrated to manage data on the machine by building digital twins of the machining process [6], [7]. Different from the digital thread that constructed in enterprise level [8], the digital twin model is usually studied in manufacturing system and equipment level. In the manufacturing system level, Zhang et al. [9] presented a digital twin-based analytical decoupling framework to provide engineering analysis capabilities and to support the decision-making over designing of the hollow glass production line. Liu et al. [10] proposed a digital twin-driven methodology for rapid individualized designing and intelligent multi-objective optimizing of both static configuration and dynamic execution of the automated flow-shop
FIGURE 2. Open architecture of DT-driven cyber-physical system for MPS.
algorithms are established. It is an effective iterative process by combining semi-physical simulation and rapid on-line joint optimization since the off-line measurement is cumbersome to accommodate for recessive and dynamic disturbances. On another hand, the deep learning research based on the experimental data is conducted for predicting micro displacement output of feedforward control function. Different from the traditional simulation architecture, the digital twin part is used as an optimization tool for optimization rather than only visual displaying and validation of simulating results. Based on the digital twin functionality of giving valuable guideline, online smart autonomously controlling can be generated in a time-efficient way.

The proposed open architecture idea is reflected by a numerical system comprising a fixed operating platform and various application modules that can be added and swapped. The platform of numerical control system is extendable for the upper-level optimization and decision-making algorithms by integrating the corresponding modules into the platform.

IV. KEY ENABLING TECHNIQUES

Actually, the research of digital twin can be divided into two major parts. The first part is to synchronize physical space and cyber space, which is introduced in the first key enabling technique. The second part is to optimize the system in cyber system and feed back to physical system, which is detailed in the last two key enabling techniques.

A. TWINNING OF CYBER AND PHYSICAL SYSTEM

The digital twin-driven cyber-physical system of MPS is resulted from the twinning between the physical punching system and a cyber model, which is realized by cyberizing the physical part for specifying the MPS components with computational abstractions/interfaces, and physicalizing the cyber model for expressing abstractions/interfaces of software components to represent dynamics of MPS timely [16]. The twinning of basic components in MPS (including the PLC-driven linear motor and middleware-based multi-type of sensors) has been discussed in our previous study [9], and thereby not detailed here for concise reason. As a critical challenge of twinning of cyber and physical system in MPS, the online detection of punched dots quality is essential to realize the adjustment of voltage control of piezoelectric ceramic to the appropriate value. Therefore, it has been discussed here in detail.

In the punching process on dense array of micro-dots, the voltage control of piezoelectric ceramic is critical, and the diameter of micro-dots is crucial. The detection system and optimizing algorithm is a precondition and also plays an important role in high quality of punching. As shown in Figure 3, this detection system includes image acquisition, image binarization, pixel edge detection, sub-pixel edge detection, circle fitting, and calibration. Firstly, the recursive Gaussian filtering is used to effectively suppress the noise. Second, Otsu’s automatic threshold segmentation algorithm is introduced to achieve high-efficiency and high-precision threshold segmentation under different material cores, light intensities, and micro-dot types. Thirdly, the Canny operator edge coarse positioning and quadratic curve fitting sub-pixel edge detection are used, and then the complete microstructure array edge contour can be extracted. Other machining status such as the loading and unloading of workpieces is twining via RFID, which will be sent to upper-level optimization system [17].

One of the keys to realize twinning of punching process is the sampling cycle of synchronization. However, the response speed of the industrial camera usually doesn’t match the highly punching speed of micro-dots (20-65 dots/sec), and thus it is difficult to monitor the process. This paper presents a method of interval image acquisition method, as is shown in Figure 4. For instance, let us denoted the micro-dots processing cycle as T(ms), and then the sampling cycle of the industrial camera is set as $nT + \frac{1}{m}$ (ms). n is determined by the response speed of the industrial camera. m is a number for equally dividing one processing cycle according to the accuracy demands of synchronization. This method prolongs the time cycle of image acquisition [18] and can realize twinning of punching process.
B. MACRO-MICRO COMPOSED CONTROL STRATEGY IN CYBER SYSTEM

Actually, the horizontal X-axis and the vertical Z-axis of MPS form a macro-micro composite platform. The X-axis is driven by a linear motor, and the Z-axis is driven by the piezoelectric ceramics (i.e., PZT) to complete the micro-dots processing. Its structure diagram and control character are shown in Figure 5. A micro actuator is designed for compensating the straightness error of the macro-motor platform in X-axis, thus forming an ultra-precise linear motion trajectory. Piezoelectric ceramics can only produce one direction of displacement, it is necessary to perceive the actual output displacement under different pretension forces of piezoelectric ceramic-driven micro-actuator. Piezoelectric ceramics have a distinctive character of hysteretic nonlinearity, namely, the output displacement of PZT at a certain moment depends not only on the current voltage input, but also on its historical input voltage value [18]. The traditional motion controller is designed according to the feedback control principle, which is difficult to meet the high-speed and high-precision requirements of the MPS.

Therefore, the platform is built by using a coordinated control and processing strategy in Figure 5. In MPS, the single linear motion axis control system can be approximated to a typical second-order system. To improve the overall performance of the machine tool, the control system adopts a compound control strategy of speed feed-forward and acceleration feed-forward to achieve “error-free adjustment”. The motor feeding motion is planned according to the S-type acceleration and deceleration curve to avoid the flexible impact of machining system. The piezoelectric ceramics complete the feed motion in the stop time of the motor. Therefore, the processing time of micro-dots structure is approximately equal to the sum of the motor running time $T_1$ and the piezoelectric ceramic feed time $T_2$.

The mathematical model can be simplified as a second-order system consisting of mass-spring-damping. The dynamic equation of X axis and Z axis can be obtained as shown in Formula (1), and the transfer function is shown in Formula (2):

$$\begin{align*}
    m_1 \ddot{y}_1 &= k_1 (u_1 - y_1) + b_1 (\dot{u}_1 - \dot{y}_1) \\
    m_2 \ddot{y}_2 &= k_2 (u_2 - y_2) + b_2 (\dot{u}_2 - \dot{y}_2) \\

    Y_1 (s) &= \frac{b_1 s + k_1}{m_1 s^2 + b_1 s + k_1} U_1 (s) \\
    Y_2 (s) &= \frac{b_2 s + k_2}{m_2 s^2 + b_2 s + k_2} U_2 (s)
\end{align*}$$

Among them, $u_1$ is the input of macro platform (force or displacement), $m_1$, $k_1$, $b_1$ and $m_2$, $k_2$, $b_2$ are the mass, stiffness, and damping coefficients of macro-motion platform and micro-motion platform, respectively. $y_1$ and $y_2$ are the displacement outputs of macro-motion platform and micro-motion platform, respectively. $U_1 (s)$ is the Laplace Transform of macro-motion platform input; $U_2 (s)$ is the Laplace Transform of micro-motion platform input. Since the motion direction of the macro-micro platform is perpendicular to the MPS, the whole system has two degrees of which is independent to each other. However, the start and stop time of the X-axis and the Z-axis need to be coordinated to complete the punching processing.

C. CONTEXT-Aware Coordinating of System and Process

The key for improving system performance on punching precision and speed is to coordinate the system controlling and punching process parameters. However, as shown in Figure 6, there exists a mismatch between the motor driver in fast time-scale and the quality measurement in slow time-scale. In a joint system controlling perspective, the complex coupling of electricity and mechanical interfaces at multiple scales usually results in lacking of dynamic adjusting capability, especially in a high punching speed of 20-65 dots/sec. Also, the nonlinear time-varying character of PZT results in a poor repeatability of punching massive micro-dots.

The punching process consists of coordinating triaxial controller for minimizing time of finishing all the micro-dots
with the performance constraints of motors and PZT. Each LGP mold consists of a chain of punching operations that is to be processed in a specified sequence among micro-dots dense array during an uninterrupted time period of given length. The conventional approach of manufacturing LGP mold is to punch the micro-dots one by one, while the high density and minimum distance among micro-dots call for ultra-precision and ultra-high speed of the machine tool. In the proposed DT-driven cyber-physical system, a novel staggered punching approach is presented, in which the micro-dots in LGP mold are punched with two or more dots of intervals. Figure 7 explains the problem and difference more specifically.

Based on the multi-domain and cross-dimension data collecting and twinning of MPS, a context-awareness [19] can be established for online autonomously controlling of system and process. Actually, it is a joint optimization with a bi-level programming structure [20], [21] comprised of upper-level staggered process parameters and lower-level MPS system control parameters. Table 1 collectively shows the basic variables (including the decision variables of triaxial controller) in the staggered punching process. Domains of decision variables and parameters are deterministic.

There is an iteration that Z-axis makes the first move by assigning feeding speed, staggered magnification of interval, voltage value and loading time of PZT, and then X-axis and Y-axis react through optimizing their own controlling parameters for the known operations including moving time, acceleration, velocity as shown in Table 1. This progress is cycled until equilibrium is obtained. The model of coordinating triaxial controller is further formulated through a bi-level programming approach.

Upper-level problem: the goal is to minimize the punching time. Meantime, the voltage control of PZT in each punching process should precisely produce a certain displacement to form micro-dots of exact depth value.

$$\min LU = \sum_{i=1}^{N} \left( \frac{1}{v_i} * s * n * (n - 1) * \left(1 + \frac{r_i}{t_i - \frac{2w_{ij}}{a_i}} \right) \right),$$

$s.t. f(u_i) = Dep.$ (3)

Lower-level problem: the goal is to minimize the stroke length of whole punching process. Meantime, the resultant velocity/acceleration of X-axis and Y-axis should be equal to staggered interval among micro-dots in each punching.

$$\min FU (t_i, a_i, v_i) = s * n * (n - 1),$$

$s.t. \left( t_i - \frac{v_i}{a_i} \right) * v_i = s * n, \quad \vec{v}_i = \vec{v}_x + \vec{v}_y; \quad \vec{a}_i = \vec{a}_x + \vec{a}_y.$ (4)

Bi-level programming is characterized by two levels of optimization problems where the constraint region of the upper-level problem is implicitly determined by the lower-level optimization problem [22]. This bi-level programming
TABLE 1. Variables in the job shop production coordination.

<table>
<thead>
<tr>
<th>Type</th>
<th>Notation</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision variables in Z-axis</td>
<td>( \omega_i )</td>
<td>Voltage of PZT</td>
</tr>
<tr>
<td></td>
<td>( s )</td>
<td>Staggered magnification of interval</td>
</tr>
<tr>
<td></td>
<td>( t_{zj} )</td>
<td>Loading time of PZT</td>
</tr>
<tr>
<td></td>
<td>( v_{zj} )</td>
<td>Feeding speed in Z-axis</td>
</tr>
<tr>
<td>Decision variables in X- and Y-axis</td>
<td>( \alpha_{ix} )</td>
<td>Acceleration of X-axis</td>
</tr>
<tr>
<td></td>
<td>( \psi_{ix} )</td>
<td>Velocity of X-axis</td>
</tr>
<tr>
<td></td>
<td>( \alpha_{yj} )</td>
<td>Acceleration of Y-axis</td>
</tr>
<tr>
<td></td>
<td>( \psi_{yj} )</td>
<td>Velocity of Y-axis</td>
</tr>
</tbody>
</table>

is a leader-follower strategy. The leader plays first, and the follower observes his action. Then, follower has to choose action of the optimal solution to \( \max FU_i \left( f_{i,j} \right) \). Finally, players get their maximal utility according to \( LU \left( e_{i,j} \right) \) and \( FU_i \left( f_{i,j} \right) \) in an equilibrium, which has been discussed in many studies [23]–[25].

Due to a non-deterministic polynomial (NP)-hard feature in this bi-level programming, it is difficult to find the equilibrium. Even though both the upper-level and lower-level problems are convex, the bi-level programming model is still possible to be a nonconvex one [26]. The solution is usually not global optimum but local optimum. Many computational intelligent algorithms [24] can achieve the optimal or near-optimal solution of this bi-level programming model via a heuristic process [20], and thus are omitted here for concise reason.

V. A DEMONSTRATIVE PROTOTYPE

A. SYSTEM IMPLEMENTATION

This paper develops a demonstrative prototype MPS machine tool. The hardware platform was built by Industrial PC and PMAC (Programmable Multi-Axis Controller). Table 2 shows the hardware part of ultra-precision MPS machine tool, and it mainly includes IMAC 400 controller, Advantech industrial PC, Parker I-310 coreless linear motor, Renishaw spacing grating ruler, Omron limit switch, piezoelectric ceramic, and its driving power.

On account of the dense features of micro-dots and the small field view of the online detection system, the grating ruler with a precision of 0.12\( \mu \text{m} \) is used as the calibration to obtain a pixel equivalent value that ensures high accuracy. The high-precision white light interferometer is used to measure the depth of micro-dots. According to the Pythagorean Theorem, the spherical radius of the tool is calculated as the diameter of micro-dots. PZT is a key driving part of the micro-feed processing of diamond cutter. Its critical performance determines the precision of the micro-dots processing. Finally, piezoelectric ceramic PST 150/14/40 is selected with empty carrier frequency 2KHz. The drive power supply is equipped with HPV~1C0150A0500. The output voltage range of the driver is 0V~150V, and the input voltage of the analog signal is 0V~10V. The technical parameters of PZT are shown in Table 3.

As shown in Figure 8, the digital twin-driven manufacturing cognitive-loop in prototype MPS named GDUT quickly translates the layout of micro-dots into the control parameters in the physical system, which greatly improves the efficiency of punching. To improve both steady state metric and dynamic metric of control system, it is tuned through adjusting PID parameters, velocity, acceleration, and friction feed-forward parameters based on digital twin. IMAC400-based motion controller is integrated into the system by calling PcommServer communication function. According to the dense array processing characteristics of micro-dots, the CNC system of the designed MPS was developed by C++ language with the Qt4.8 development environment. A simple and easy-to-use high-precision in-position detection system is designed with the joint programming of Halcon and MFC.

B. SYSTEM PERFORMANCE

Table 4 shows a comparison of among optimized digital twin-driven MPS (i.e., DT-MPS), main stream machine tools, and a formerly-developed original prototype MPS in our Lab.
TABLE 4. Metrics comparison of MPS machine tools.

<table>
<thead>
<tr>
<th>Metrics</th>
<th>Main Stream</th>
<th>Prototype MPS</th>
<th>DT-MPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z-axis stroke (mm)</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Z-axis Accuracy (µm)</td>
<td>±0.5</td>
<td>±0.4</td>
<td>±0.4</td>
</tr>
<tr>
<td>XYZ straightness</td>
<td>±5µm/200mm</td>
<td>±2µm/200mm</td>
<td>±2µm/200mm</td>
</tr>
<tr>
<td>Punching Speed (dots/sec)</td>
<td>20–40</td>
<td>20–25</td>
<td>20–65</td>
</tr>
<tr>
<td>Position accuracy (µm)</td>
<td>±1</td>
<td>±2</td>
<td>±1</td>
</tr>
<tr>
<td>Punching depth (µm)</td>
<td>2–9</td>
<td>2–8</td>
<td>2–8</td>
</tr>
</tbody>
</table>

Mold steel, 7075 aluminum alloy and brass that with high hardness and ideal wear resistance characters are selected as the material for experiment. Coupled machining experiments of diamond cutters and different material are performed on a precision punching machine tool of dense microstructure arrays to obtain micro-dots of different types, including circular equidistant, circular misalignment and circular tangent. The white light interferometer is used to analyze the processing quality and accuracy of the three-dimensional topography of the micro-dots. The errors existing in the processing of dense arrays of micro-dots have been analyzed and compensated. Experiments of the displacement output of piezoelectric ceramics at different given voltages and the actual amplification factor of piezoelectric actuators are conducted.

Through machining experiments, it is verified that the digital twin-driven compensation of piezoelectric ceramics can improve the accuracy of micro-dots. Generally, the punching speed and position accuracy of the micro-dots processed on the optimized DT-MPS machine tool are better than the original Prototype MPS. The proposed digital twin-driven CPS directly conducts execution logic validation and control in the digital model of MPS, quickly locates the malfunction reason, and proactively inspects the system whether can meet the quality controlling requirement. As a result, the positioning accuracy of initial prototype MPS machine tools has been improved from the 4.0 µm to 2.0 µm after implementing digital twin-driven CPS. The punching speed is improved from 20-25 dots/sec to 20-65 dots/sec, and also superior than main stream machine tools that of 20-40 dots/sec. The machining experimental results are consistent with the actual requirements, which shows that the developed digital twin system is applicable for the machining of micro-dots in ultra-precision machine.

Actually, compared to the original prototype MPS, the optimized DT-MPS is superior in the punching speed and position accuracy, which are two most important metrics in the mass production. This improvement results from the adopting of digital twin approach in the MPS. The reason of same results in other metrics such as punching depth is that these manufacturing capabilities are depended on the inherent nature of the main body and hardware components of MPS, which remains unchanged compared to the original prototype MPS.

VI. DISCUSSIONS

The positioning error compensation principle of IMAC400 motion controller is to create an equal displacement which is opposite to original error of the system. Taken positioning error of X-axis as an example to explain. The working stroke of the X-axis is -125mm to 125mm, and the measurement takes one point in each 5mm interval and obtains a total...
of 50 test points. Each anchor point is paused 5 seconds to obtain the accurate position. The measurement is repeated 3 times. In the data collection process, Renishaw LaserXL analysis software of the laser interferometer is simultaneously used to analysis curve to obtain the positioning error curve of the X-axis. Positioning accuracy of the conventional approach is shown as the upper-part in Figure 9.

According to the analysis results, the two-way positioning error range of X-axis on the 250mm working stroke is 24.57 µm, and the positioning accuracy is 0.17 µm. As for direct driving linear motor, there is generally no reverse gap. As shown in upper part of Figure 9, there is not much difference between positive and negative position error of linear motor. Therefore, only the pitch compensation of X-axis is required. After adopting the proposed digital twin-driven CPS approach in MPS, the positioning accuracy and error curve of X-axis compensation was measured as shown in lower-part of Figure 9. By timely compensation, the positioning error range of the X-axis on the 250mm working stroke is reduced to 2.0 µm.

With respect to the consistency evaluation of Z-axis, the actual output displacement of piezoelectric ceramics needs to be dynamic compensated under a different input voltage value in the punching process. The experiment scenario is designed as: dense-array of micro-dots with an average diameter of 45 µm and depth of 4.5 µm. The distance between the tip of diamond blade and the die core is 0 µm, and the spring absorbs 10 µm. The piezoelectric ceramics needs to be fed with 24.5 µm. The conventional compensation strategy directly determines the displacement output of piezoelectric ceramics by using the simulated input. However, in the proposed digital twin-driven processing compensation, the non-linearity of piezoelectric ceramics compensates through online optimized input value of piezoelectric ceramics.

The micro-dots punching diagram with conventional compensation is shown in upper-part of Figure 9, which changes obviously over time. The processing effect diagram after adopting of proposed digital twin-driven processing compensation is shown in lower-part of Figure 9. The diameter error of the micro-dots decreases from 2.226 µm to 0.396 µm. In the conventional compensation of piezoelectric ceramics, the simulated input amount of the piezoelectric ceramic driver is fixed 572. After adopting of proposed digital twin-driven processing compensation, the voltage input amount of the piezoelectric ceramic driver is around 640. Because of the nonlinear convex curve of piezoelectric ceramics, the voltage amount of the piezoelectric driver input is relatively larger than that in conventional the compensation process. The improved precision of the average diameter of the micro-dots array verifies the feasibility of the online nonlinear compensation in the process.

Adopting digital twin helps MPS to make smarter control decision [27]. The digital twin-driven cyber-physical system platform can optimize dynamic execution mechanism. The performance of the whole CPS can be virtually analyzed and feedback to the physical system. Once a deficient performance, the operating can be adjusted and iterated until obtain the optimal status. Context-aware solution in equipment level is formed, and all the control decisions of machines are evaluated and made using the contextual analytics method. The proposed CPS model is relatively flexible by enabling each MPS of online setting with different individualized machining parameters and quality requirements, which provides a large variant of options to meet the individualized demands.

There remains many limitations waiting to be solved. The first limitation is lacking of more engineering analysis ability and robust decision support, which needs to incorporate big data analytics [28] and information fusion techniques [29]. When compared the cyber system with actual manufacturing result, the deep-fusion of digital twin model with deep learning algorithm [30] can be introduced to identify whether there is a difference and find out the cause [28]. For the micro-dots with sparsity and random distribution feature, there exists a higher-level of joint optimization between configuration of job conditions and collaborative optimization of job path. Other complex situations such as position error zeroing, multiple PZT headers, and multiple optimization objectives can be furtherly researched to achieve a good performance on robustness. Once the data collected from the MPS reaching a certain volume, artificial techniques including granular computing [31], parallel processing [32] and its hybrid models [33] can be introduced into the optimization section in digital twin model [34].

VII. CONCLUSIONS

This paper takes the micro punching system as implementation scenario and presents an open architecture of digital twin-driven cyber-physical system. Key enabling techniques are detailed. Digital twin defines the performance metrics to support online optimizing and provides a context-aware adaptability to change. Evidenced by a successful prototype of digital twin-driven micro punching system, the proposed approach can provide numeric control system design with a new vision. The limitations arise from the fact that it lacks a higher-level engineering analysis ability for a better autonomously control. The technological intersection of CPS
and artificial intelligence technique is a critical area to be further tackled for a smart machine tool. Moreover, mining and automating decision-support knowledge from the context are supposed to be major challenges for achieving self-adaptive control in machining.

REFERENCES


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