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RESEARCH ARTICLE

Unified modelling for continuous–discrete hybrid adaptive machining CPS of large thin-walled parts

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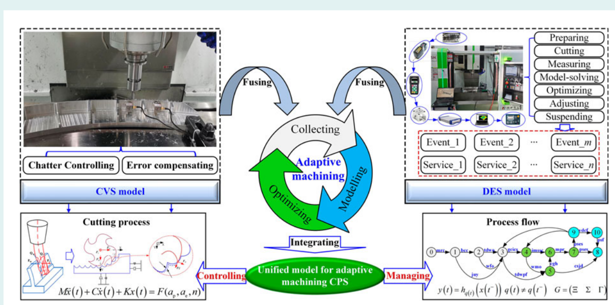
ABSTRACT

Traditional machining is transforming to digital and intelligent machining, in which adaptive machining cyber-physical system (CPS) provides a useful approach to control the machining quality of large thin-walled parts. And the running of adaptive machining CPS is a complex multi-processes execution flow, which can be regarded as a continuous–discrete hybrid system. To realise adaptive controlling of machining quality and adaptive managing of process flow, a unified model for continuous–discrete hybrid adaptive machining CPS is constructed. Firstly, an architecture of adaptive machining CPS is proposed. Next, the cutting process in adaptive machining CPS is modelled as a continuous-variable system (CVS), while the process flow in adaptive machining CPS is modelled as a discrete-events system (DES). Then, the finite state machine is adopted to integrate the CVS and DES to form the unified model of adaptive machining CPS. Finally, an adaptive machining CPS is developed based on the unified model, and the machining results demonstrate that machining quality is efficiently controlled, as well as the process flow is orderly managed. The built unified model has four features, respectively universality, integrability, scalability, and reconfigurability, which can be reconstructed to form a new instancing model according to the different machining requirements.



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KEYWORDS
Unified model; continuous–discrete hybrid system; adaptive machining CPS; large thin-walled parts; integrating modelling

1. Introduction

Large thin-walled parts (in short LTWP) are widely served in aerospace manufacturing due to their high strength-mass ratio (Herranz et al. 2005 and Irene et al. 2019). And the machining quality of LTWP directly influences the performance of aerospace vehicle. However, two problems, machining chatter (Zhao, Zheng, and Yu 2022), and thickness error (Zhao, Zheng, and Zhang 2021) are usually generated due to the low-stiffness of LTWP, and they seriously restrict the machining quality of LTWP. To cope with these problems, adaptive machining technologies are proposed (Zhang et al. 2020, 2021), which follow the close-loop of 'measuring-feedback-optimising-machining'. Actually, the adaptive machining process of LTWP can be regarded as a complex multi-operations flow, in which the locating, measuring, analysing, optimising, cutting, etc., are dynamically executed and adjusted according to the actual requirements. Specifically, on the one hand, the generated machining problems are timely solved by adaptive process optimisation, and on the other hand, the process flow is orderly managed by configurating operations and rules. Thus, two objectives, that adaptive machining quality controlling, and adaptive machining

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process flow managing, need to be realised to guarantee the effective and smooth execution of all operations. Cyber-Physical-System (CPS), that integrates computing, communication, and control, on the basis of sensor technology, provides a useful way to realise of adaptive manufacturing system (Chen et al. 2015). Lots of scholars have concentrated on the CPS modelling of a manufacturing system. Wang (2013) built a CPS for the machining process, which could realise distributed process-planning, real-time process-monitoring, and remote system-controlling. Wan et al. (2013) established a CPS for machine tool by using the Internet of Things (IoT) and a multi-sensory network. Lee, Bagheri, and Kao (2015) pointed out that the technology of big-data analysing is the key to build CPS for the machining process. Tong et al. (2020) put forward a CPS of the intelligent CNC machine tool, which could optimise tool-path based on the dynamic of machine tools. Liu, Zheng, and Xu (2021) proposed a framework for cyber-physical machine tools for the digitalisation and servitisation of future generation machine tools.

It can be obtained that most of the researches built a manufacturing CPS to solve the specific problem based on the common architecture. And the running principle of CPS can be concluded as: variables are controlled by execution of operations. From the perspective of the continuous–discrete hybrid system, the controlled variables are continuously varied during machining, such as machining chatter and error, and a continuous-variable system (CVS) is used to model this variables-varying process. Whereas, the operations are interactively executed in discrete time points based on defined rules, which is modelled as a discrete-events system (DES). Thus, the adaptive machining CPS of LTWP belongs to a continuous–discrete hybrid system (Linkens and Yang 1996). Many scholars have researched the CPS from the CVS and DES respectively.

Research on continuous-variable system. The researches about the CVS concentrate on solving machining problems to control machining quality, particularly, overcoming chatter and error. And they usually follow the close-loop of 'measuring-feedback-optimising-machining' (Lacalle et al. 2007; and Aurrekoetxea et al. 2022). To solve machining chatter, two kinds of methods are usually employed, respectively, using damper fixture (Santiago et al. 2020; Antonio et al. 2021; and Casuso et al. 2022) and optimising cutting parameters (Campa, Lacalle, and Celaya 2011). And the second approach is commonly adopted due to the convenient and low-cost implementation. With this idea, Urbikain and Lacalle systematically researched chatter modelling and suppression, their researches covered machining process monitoring (Lacalle et al. 2005 and Urbikain and Lacalle 2020), chatter modelling and suppressing for barrel cutters-milling (Urbikain, Olvera, and Lacalle 2017, 2018) and turning (Urbikain et al. 2015, 2016), even roughness modelling was also studied (Arizmendi et al. 2009 and Urbikain et al. 2021). The built models in these researches provided useful ways to deal with machining chatter. Budak et al. (2012) divided the milling process of the blade into several process steps (PSs), and calculated stable lobe diagram (SLD) to optimise the cutting parameters. Tuysuz and Altintas (2017) predicted the chatter based on the technology of reduced-order sub-structure synthesis, which was used to optimise cutting parameters for chatter suppression. Deng et al. (2020) proposed a reliability analysis of the milling system with uncertainties to predict reliable chatter-free machining parameters. Furthermore, several scholars also point out machining chatter is influenced by fluctuation amplitude and frequency of cutting force, and this factor should be considered (Wang et al. 2022; Tang et al. 2022 and Mo et al. 2022). To solve the machining error, Aurrekoetxea et al. (2022) made a comprehensive review of error modelling and compensating, and point out error data monitoring was necessary to provide feedback for its compensation. Lacalle et al. (2007) compensated machining error of complex surface milling by tool-path selection. Huang et al. (2014) evaluated the machining error based on on-machine measurement (OMM), and compensated the machining error by tool-path modification. Liu et al. (2015) integrated the OMM with the CNC system, which was used to reconstruct machining face with measurement data. Huang et al. (2018) proposed a first-order iterative error prediction method. Ge et al. (2020) developed a zero-point modification system based on the OMM. Hou et al. (2019) proposed a first-order error compensation method to control the machining error. From the above analysing, the researches about CVS provide a good way for adaptive controlling of machining quality. And the general idea of CVS researches lies in maintaining timely follow-up with the current cutting condition by parameters optimising.

Research on discrete-events system. The researches about DES concentrated on adaptive managing process execution. Generally, three elements are contained in the DES, respectively services, discrete events, and rule engine. The services represent the typical operations in the process flow, and the discrete events mean a series of states occurred at the discrete time point, which are used to trigger the execution of the services (Estruch, José, and Heredia 2012 and Esmaeilian, Behdad, and Wang 2016). Rule engine specified the logical relationship between the services and events. Based on this conception, it is a good idea to automatically execute the whole machining process flow (Zhao, Zheng, Wang, et al. 2022), which includes planning, milling, measurement, and optimisation, etc., by the service definition, triggering and processing. This idea belongs to process planning and execution under service-oriented architecture (SOA) (Wang, Ghenniwa, and Shen 2008). Under this architecture, four common tools are usually employed to modelling the process flow, respectively business process modelling notation (BPMN), petri net (PN), function block (FB) and finite state machine (FSM). BPMN is a more comprehensive graphical modelling language for high-level business flow analysing, and it is mainly used to model the complex business processing (Arevalo et al. 2016 and Zarour et al. 2020). PN models the logical relationship of states in workflow, and it is mainly used in the top design stage (Rosa, Barbosa, and Teixeira 2019 and Lee and Kim 2021). FB realised the packaging of a specific function, and the workflow could be quickly organised by FB configured. FB is widely used in CNC machining (Wang, Hao, and Shen 2007; Mourtzis et al. 2016 and Adamson, Wang, and Moore 2017). FSM emphasises state transfer and workflow execution, and it not only details the state transfer rule, but is also good at workflow adjustment and extension (Wang, Zheng, and Wang 2021 and Southier et al. 2022). Thus, it is a suitable method to model the automation execution of adaptive machining process flow.

According to the above analysing, three conclusions can be drawn: (1) CVS is used to solve specific machining problems and control machining quality, while DES is applied to manage the machining process flow and various operations. Adaptive machining CPS belongs to a continuous–discrete hybrid system. Thus, how to integrate models of CVS and DES is one model is necessary to support the implementation of CPS. (2) The adaptive machining CPS will be more complex along with the size and structure-complexity of LTWP increasing, and usually many manual interactive operations are inevitably occurred. In this context, it is very difficult to smoothly manage and control the machining CPS without a general and fundamental mechanism and corresponding model. Thus, if a theoretical model of adaptive machining CPS can be established by mathematical method, the logical relationship between CVS and DES, as well as services and events can be clearly defined. And this will be of great significance for the management and control of adaptive machining CPS of LTWP. (3) The running mechanism of adaptive machining CPS is almost the same, that is continuous variables are controlled by the execution of services, and the execution of services is triggered by discrete events and constrained by specific rules. With this principle, how to construct a basic model, and quickly form a new model based on the basic model for the specific adaptive machining CPS is also important for different adaptive machining CPSs.

Based on the above three conclusions, it is a worthwhile study to construct a unified model for automatically controlling and managing various adaptive machining CPS, so that the complex machining process and activities are controlled and managed efficiently. However, few studies have been reported on such a theoretical model and its practices. Therefore, this paper mainly tries to propose a unified modelling method for adaptive machining CPS of LTWP by incorporating the theory of a hybrid system. It provides a comprehensive tool for adaptive control machining quality and adaptive management process flow.

2. Adaptive machining CPS for machining chatter and thickness error controlling

This section first gives an adaptive machining CPS architecture, and then details the adaptive quality controlling algorithm, including solving machining chatter and thickness error. Finally, the running principle of CPS is analysed to provide theoretical support for unified CPS modelling.

2.1. Adaptive machining CPS for LTWP

Adaptive machining CPS is useful for solving machining chatter and thickness error of LTWP. Following the close-loop process flow of 'measuring-feedback-optimising-machining', Figure 1 firstly illustrate a CPS architecture.

Five layers are contained in this architecture, including the equipment layer, data layer, model layer, optimisation layer, and application layer. The equipment layer clears hardware and software employed in CPS. The data layer details the theoretical and actual data related to LTWP. The model layer is used to model the time-varying information of LTWP. The optimisation layer details the adaptive process optimisation algorithms. And application layer builds an adaptive machining CPS, including hardware and software, to control and manage the complex adaptive machining system. In Figure 1, the down-layer provides the fundament for the up-layer, and the top-layer is used to control and manage the whole CPS.

Generally, three 'C' technologies loop is adopted to describe a CPS, respectively Communication, Computation, and Control, shown in Figure 2. In adaptive machining CPS, 'Communication' means the data collection and transferring between the cyber- and physical-space, 'Computation' refers to the information modelling based

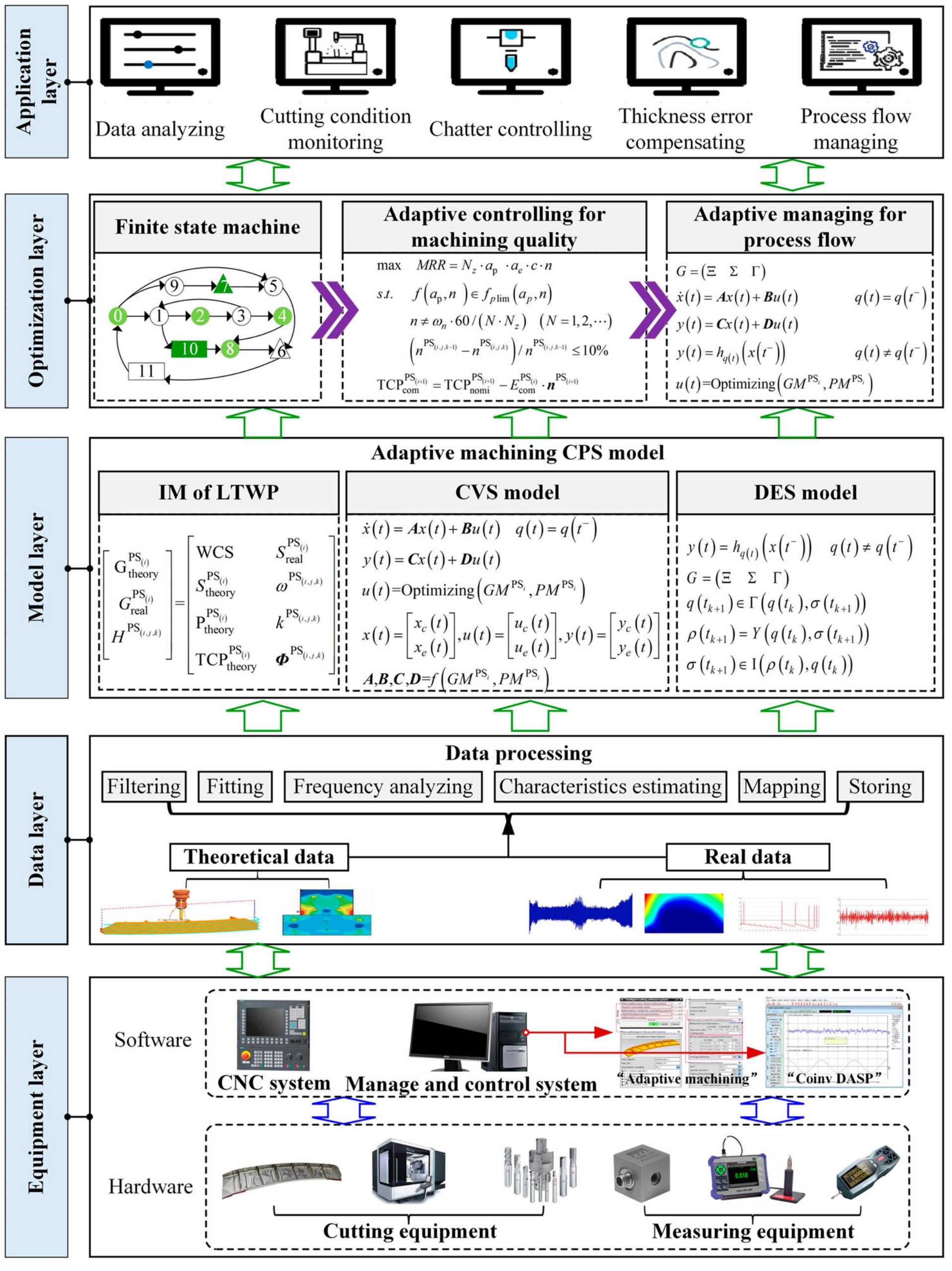

Figure 1. Architecture for adaptive machining CPS of LTWP.

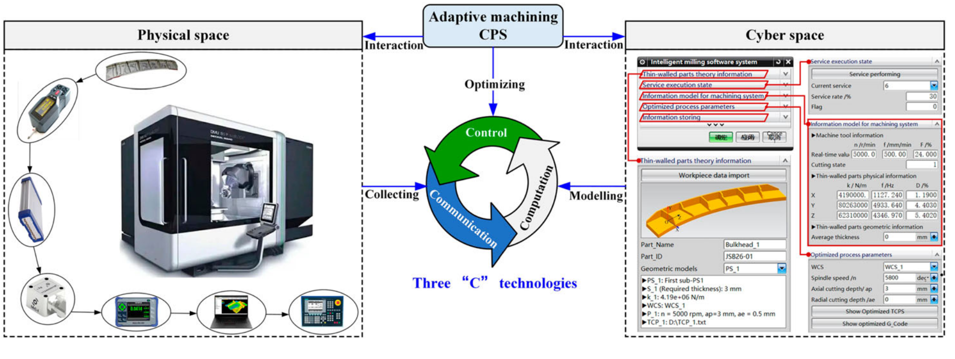

Figure 2. Adaptive machining CPS for LTWP.

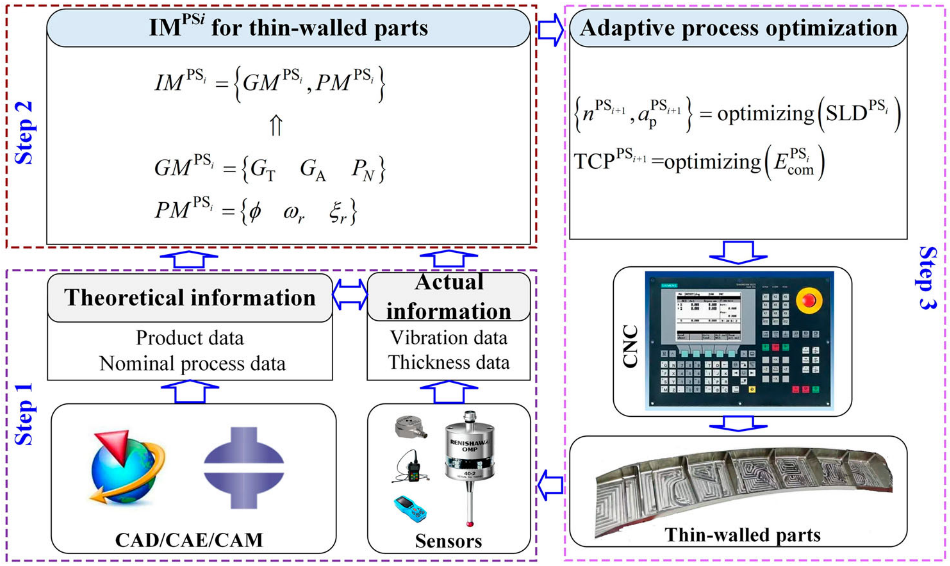

Figure 3. Adaptive machining of LTWP for solving machining chatter and error.

on collected data, and 'Control' is used to control machining chatter and thickness error. Three 'C' are looped to realise adaptive machining.

Mapping the CPS architecture to the three 'C' looping, the equipment-layer is taken as physical space, data-, model- and optimisation-layers are matched to the cyber space, and application-layer is corresponded to the control and manage system. Figure 2 builds an adaptive machining CPS for LTWP. In this system, the physical space performs the adaptive machining, and the cyber space controls the machining process based on the process optimisation model and process flow model. The physical- and cyber-spaces are communicated with each other with the collected data and optimised cutting parameters. Two objectives are realised for adaptive machining CPS, respectively adaptive controlling for machining quality, and adaptive managing for process flow.

2.2. Adaptive controlling of machining chatter and thickness error for LTWP

Adaptive machining CPS is run based on adaptive machining technologies, and the algorithms for solving machining chatter and thickness error are detailed by the authors team (Zhao, Zheng, and Yu 2022; Zhao, Zheng, and Zhang 2021). Thus, after building the adaptive machining CPS of LTWP, the running algorithm of the CPS is generally divided into three steps, shown in Figure 3.

Step 1 Data collecting. Theoretical and actual information for LTWP are collected. Theoretical information, included product data and nominal process data, are obtained by the CAD/CAE/CAM. Product data refers to the name, ID and material property, while the nominal process data covers theoretical geometric data and nominal cutting parameters. Actual information included actual geometric and physical data, are measured during cutting process with sensors, such as the data of thickness and machining vibration.

Step 2 Information model constructing. After data collecting, the geometric information of LTWP is modelled by theoretical geometric data G_T, actual geometric data G_A, and nominal process data P_N, expressed as Equation (1). In Equation (1), the theoretical and actual geometric model of LTWP is fitted based on G_T and G_A. And the fitted model is used to calcualte the machining error of LTWP.

$$GM^{\mathrm{PS}_i} = \{G_\mathrm{T}, G_\mathrm{A}, P_\mathrm{N}\} \tag{1}$$

The physical information of LTWP is modelled by FEA and optimised STD method (Zhao, Zheng, and Yu 2022), espressed as Equation (2). The physical information mainly contained modal shape $\boldsymbol{\varphi}$ that calculated by FEA, modal frequency ω_r and damping ratio ξ_r, that are estimated with machining vibration data by optimised STD method. The frequency response function (FRF) of LTWP is derived based on the above parameters.

$$PM^{\mathrm{PS}_i} = \{\phi, \omega_\mathrm{r}, \xi_r\} \tag{2}$$

After that, the information model (IM) of LTWP that contained geometric and physical information is constructed as Equation (3). The IM represents the current cutting condition of LTWP.

$$IM^{\mathrm{PS}_i} = \{GM^{\mathrm{PS}_i}, PM^{\mathrm{PS}_i}\} \tag{3}$$

Note that the superscript PS_i refers to the parameters belongs to process step i, which is used to remove a layer material of LTWP.

Step 3 Process optimising and executing. After information modelling of LTWP, firstly, the error compensated value $E_{com}^{PS_i}$ is calculated based on GM^{PS_i} and PM^{PS_i} (Zhao, Zheng, and Zhang 2021), and the stability lobe diagram (SLD^{PS_i}) is obtained by PM^{PS_i} (Zhao, Zheng, and Yu 2022). Then, the process optimising models for solving machining chatter and thickness error are built, and they are respectively expressed as Equations (4) and (5).

$$\{n^{PS_{i+1}}, a_p^{PS_{i+1}}\} = \text{optimizing}(SLD^{PS_i}) \quad (4)$$

$$TCP^{PS_{i+1}} = \text{optimizing}(E_{com}^{PS_i}) \quad (5)$$

In which, $\{n^{PS_{i+1}}, a_p^{PS_{i+1}}\}$ are spindle speed and axial cutting depth for PS_{i+1}, and they are selected. $TCP^{PS_{i+1}}$ is tool centre point for PS_{i+1}.

The optimised cutting parameters are obtained by submitting the *IM* into the process optimising model. Then, the PS_{i+1} is executed with the optimised cutting parameters, so that the machining quality can be controlled. In this paper, the cycle of 'measuring-feedback-optimising-machining' is adopted, and the in-process data in this process step is used to optimise the process parameters of the next process step. In this way, the *IM* of LTWP is obtained based on actual geometric and physical data, which can accurately represent actual cutting conditions. Thus, the optimised cutting parameters can maintain timely traceability for the current cutting condition.

It should be noted that, this paper mainly tries to construct a unified model that integrated CVS and DES. The theme of this work is 'Manufacturing Modelling, Management and Control', and both the information for machining quality controlling and process flow managing should be considered in the model. Thus, the specific algorithms for chatter controlling and error compensating are not detailed, and they can be fined in our previous researches (Zhao, Zheng, and Yu 2022; and Zhao, Zheng, and Zhang 2021).

3. Unified modelling for adaptive machining CPS of LTWP

Actually, the architecture of adaptive machining CPS in Figure 1 is also universal for other adaptive machining technologies. In other words, this is a unified architecture for most of the adaptive machining methods. Thus, it is a worthwhile study to construct a unified model for adaptive machining CPS to realise adaptive controlling machining quality and adaptive managing process flow. This section is organised to propose a unified model for adaptive machining CPS of LTWP.

3.1. *Multi-processes flow for adaptive machining CPS*

The running principle of unified architecture in Figure 2 can be regarded as a close-loop process flow, which is circulated among several typical states, shown in Figure 4(a). Here, seven states are defined for the process flow, respectively preparing state, cutting state, measuring state, modal-solving state, optimising state, adjusting state, and suspending state.

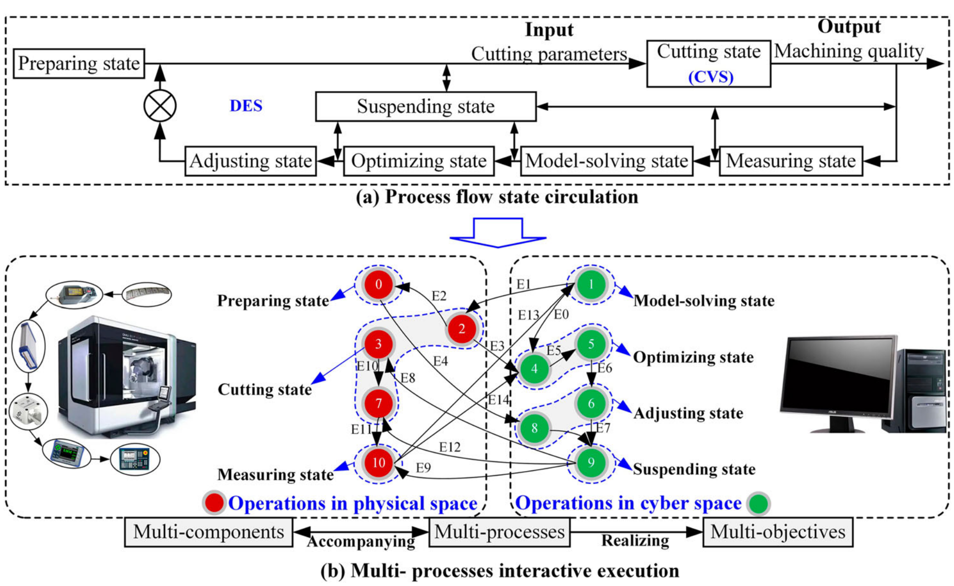

Figure 4. Multi-process execution flow for adaptive machining CPS.

Each state will include several operations, for example, both the vibration data and thickness data collecting belongs to the measuring state (Figure 4(b)). Moreover, the execution of operations is triggered by the generated events, for example, when E9 (events for cutting starts) is generated, the operations-10 (Vibration data collecting) is executed. And when E13 (events for cutting finished) is generated, the operation-1 (Physical modelling) is executed. Thus, when the operations and events are defined for adaptive machining CPS, the multi-operations flow is formed based on specific rules. When this multi-operations flow executes, the adaptive machining CPS is running, and the hardware and software in the CPS are parallel controlled to perform specific actions(Figure 4(b)).

In this multi-operations flow, three characteristics are concluded, respectively multi-components interaction, multi-processes interactive execution, and multi-objectives achievement. Multi-components include machine tool, LTWP and several kinds of sensors. Multi-processes mean that multi-operations are interactively executed in the process flow. Multi-objectives represent machining quality controlling, and process flow managing. Actually, these three characteristics are contained in most adaptive machining systems, and this improves the complexity of process flow managing. Thus, it is necessary to construct a unified CPS model to guide multi-processes acted on multi-components to realise multi-objectives, so that both the machining quality and process flow can be controlled and managed in adaptive machining CPS.

3.2. Continuous–discrete hybrid adaptive machining system for LTWP

Adaptive machining CPS is a complex multi-operations execution flow. From the perspective of the complex system, a continuous variables system (CVS) and discrete events system (DES) have simultaneously existed in CPS, shown in Figure 4. The chatter and thickness error are continuous variables in CVS, and the typical operations of the machining system are a series of services in DES. The services are accompanied by discrete events and rules. The continuous variables are controlled by the execution of services, and the execution of the service is triggered by discrete events and constrained by specific rules. Thus, adaptive machining CPS can be regarded as a continuous–discrete hybrid system. Thus, the CVS and DES are firstly defined and modelled.

CVS definition and modelling. The cutting process of LTWP is regarded as CVS, expressed as Equation (6), in which, the machining chatter and error are easily occurred and continuous varied due to the time-varying cutting condition of LTWP.

$$\boldsymbol{M}\ddot{\boldsymbol{x}}(t) + \boldsymbol{K}\dot{\boldsymbol{x}}(t) + \boldsymbol{C}\boldsymbol{x}(t) = F(\boldsymbol{u}(t)) \tag{6}$$

where $\boldsymbol{M}$, $\boldsymbol{K}$, $\boldsymbol{C}$ are respectively mass, stiffness and damping matrix, $\boldsymbol{F}$ is the cutting force, $\boldsymbol{u}(t)$ is optimised parameters.

The cutting condition of LTWP is continuously changing due the material removal. An accurate model of CVS is key to ensuring the optimised parameters can timely track the current cutting condition. Thus, it is necessary to model CVS in adaptive machining CPS to control machining quality of LTWP. With this idea, the chatter state $x_c(t)$ and error compensated process $x_e(t)$ are defined as continuous variables, and the feedback-control method is usually employed to optimise cutting parameters based on the time-varying information model. Here, the state space model of feedback control is constructed for CVS, which is expressed as

$$\begin{cases} \dot{x}(t) = \boldsymbol{A}x(t) + \boldsymbol{B}u(t) \quad q(t) = q(t^-) \\ y(t) = \boldsymbol{C}x(t) + \boldsymbol{D}u(t) \\ u(t) = \text{Optimizing}(GM^{\text{PS}_i}, PM^{\text{PS}_i}) \\ x(t) = \begin{bmatrix} x_c(t) \\ x_e(t) \end{bmatrix}, u(t) = \begin{bmatrix} u_c(t) \\ u_e(t) \end{bmatrix}, y(t) = \begin{bmatrix} y_c(t) \\ y_e(t) \end{bmatrix} \\ \boldsymbol{A},\boldsymbol{B},\boldsymbol{C},\boldsymbol{D} = f(GM^{\text{PS}_i}, PM^{\text{PS}_i}) \end{cases} \tag{7}$$

In which, $x(t)$ is continuous variables, including $x_c(t)$ and $x_e(t)$. $y(t)$ is machining result. $u(t)$ is the optimised cutting parameters, that are obtained with Equations (4) and (5). $q(t) = q(t^-)$ means that the process flow is running in one discrete time node (staying in one state). $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$, $\boldsymbol{D}$ are coefficient matrices related to the information model of machining system, and are calculated through $f(\cdot)$ based on the information model of LTWP.

In this paper, when machining chatter is controlled, the coefficient matrices are calculated as

$$\boldsymbol{A} = \begin{bmatrix} 0 & \boldsymbol{I} \\ -\boldsymbol{M}^{-1}\boldsymbol{K} & -\boldsymbol{M}^{-1}C \end{bmatrix}, \boldsymbol{B} = \begin{bmatrix} 0 \\ \boldsymbol{M}^{-1} \end{bmatrix}$$
$$\boldsymbol{C} = [1, 0], \boldsymbol{D} = [0, 0] \tag{8}$$

when the thickness error is compensated, these matrices are calculated as

$$\boldsymbol{A}_c = \left[\frac{1}{E_{\text{com}}}, 0\right], \boldsymbol{B}_c = [-S_{\text{real}}, 0]$$
$$\boldsymbol{C}_c = [1, 0], \boldsymbol{D}_c = [0, 0]$$

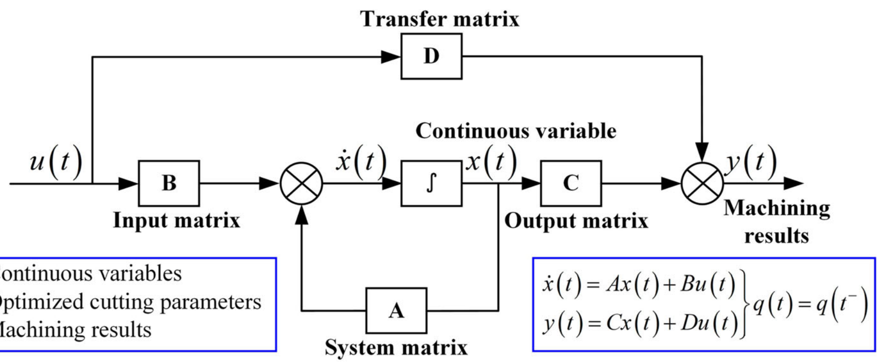

Figure 5. Running principle (state space model) of CVS.

$$E_{\text{com}} = \alpha_i \cdot \Delta d, \quad \alpha_i = g(\boldsymbol{K}, \boldsymbol{S}_{\text{real}}) \tag{9}$$

In which, E_{com} is error compensated value, S_{real} is real thickness after machining, Δd is thickness error, and α_i is error compensated coefficient, which is calculated by Zhao, Zheng, and Zhang (2021).

Equation (9) gives the continuous variables-controlled algorithm and the adaptive controlling for machining quality can be realised with this model. It is worth noting that this state space model is also suitable for the variables in other machining processes, and $x(t)$ can represent other variables. Actually, most of the existing researches about adaptive machining can be modelled with Equation (9). Based on Equation (9), The running principle of CVS is illustrated in Figure 5.

DES definition and modelling. Three elements are contained in DES, respectively services, discrete events, and rule engine. When a discrete event occurs, the related service will be executed according to defined rules to control the continuous variables. Thus, the multi-operations flow can be regarded as a services flow. The following text gives the definition of these three elements.

1) Services: The typical operations are defined as services, and they were expressed as

$$ServiceName\begin{Bmatrix} StateAffiliation, ServiceID, \\ ServiceInput, ServiceOperation, \\ ServiceOutput, ServiceFlag \end{Bmatrix} \tag{10}$$

In which

- *ServiceName* is a service class, and the ServiceName is defined as the name of an operation.
- *ServiceAffiliation* indicates which flow state is belonged to for the service.
- *ServiceID* is the unique ID for service, which is obtained based on the *ServiceName* and its executing time, expressed as *ServiceName_Year_Month_Day_Hour_Minite_Second*.
- *ServiceInput* represents the input variables required for service execution.
- *ServiceOperation* represents the operation of the current service.
- *ServiceOutput* represents the output after service execution.
- *ServiceFlag* $= 0/1$ means that the service execution is incomplete or completed.

Based on the above definition, typical operations in adaptive machining CPS (solving machining chatter and thickness error) are encapsulated as different services, which are listed in Appendix 1. These services can be reorganised and configured according to different machining requirements.

2) Discrete events: The flags occurred during adaptive machining are defined as discrete events, such as milling starting and finishing, measuring starting and finishing, etc. The discrete events are generated after services execution, and triggered the execution of services. Expressed as

$$EventName(EventAffiliation, EventID, EventFlag) \tag{11}$$

In which

- *EventName* represents an event class, and *EventName* is the name of discrete events.
- *EventAffiliation* indicated which flow state is belonged for the specific events.
- *EventID* is the unique ID of an event. which is obtained based on the *EventName* and its execution time, expressed as *EventName_Year_Month_Day_Hour_Minite_Second*
- EventFlag $= 0/1$ means that an event has not occurred or occurred.

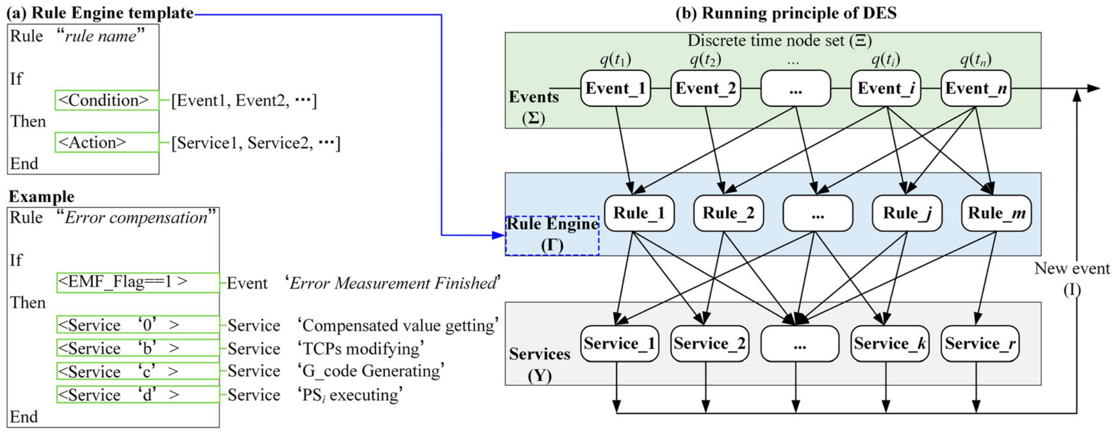

Figure 6. Rule engine template and running principle of DES.

According to the above definition, the typical services and discrete events for adaptive machining CPS (solving machining chatter and thickness error) are listed in Appendix 2, and these services and events are usually coupled with each other.

3) Rule engine: The rule engine defines the process flow running principle. In DES, the discrete events are used to trigger the execution of services. Thus, the rules between services and discrete events are concluded as: if events in the $<$Condition$>$ meet the rules, *Services* in the $<$Action$>$ are triggered. Figure 6 (a) shows the rule engine template for the adaptive machining CPS.

The above three elements are key components of DES. The model of DES clearly displays the relationships between services, discrete events, and rules, which can provide guidance for process flow managing. Thus, when these three elements are defined, the DES model for adaptive machining CPS can be uniformly constructed, and expressed as Equation (12).

$$\begin{cases} y(t) = h_{q(t)}(x(t^-)) \qquad q(t) \neq q(t^-) \\ G = \begin{pmatrix} \Xi & \Sigma & \Gamma \end{pmatrix} \\ q(t_{k+1}) \in \Gamma(q(t_k), \sigma(t_{k+1})) \\ \rho(t_{k+1}) = Y(q(t_k), \sigma(t_{k+1})) \\ \sigma(t_{k+1}) \in \mathrm{I}(\rho(t_k), q(t_k)) \end{cases} \tag{12}$$

In which, $q(t) \neq q(t^-)$ means that the process flow is transferred from the current state to another state, and in this case, the continuous variables are varied following the new output function $h_{q(t)}$, which are calculated according to current services execution function. $\Xi = \{q(t_1), q(t_2), \ldots, q(t_n)\}$is a set of discrete time nodes, which represent the time node that discrete events occurred. $\Sigma = \{\sigma_1, \sigma_2, \ldots, \sigma_n\}$ is events set defined in Appendix 2. Γ is the flow state transfer function, which is defined based on the rule engine. Y is the service execution function for each service, which is constrained by the rule engine template, $\rho(t_k)$ is services executed results and finished flag. I is the discrete events generation function, new events are generated with the services executed results. Note that only the DES for controlling chatter and error are modelled here, and the services, discrete events, and rules for other machining problems can also be defined and integrated into Equation (12). In other words, Equation (12) has universal nature for various machining systems.

After the definition of DES, Figure 6(b) illustrates the running principle of DES. It can be obtained that service execution is triggered by discrete events, and the result after service execution is used to generate new events. The rule engine is used to constrain the execution of services.

3.3. *Unified CPS modelling based on FSM*

When models of CVS and DES are obtained, they are integrated to build the continuous–discrete hybrid adaptive machining CPS for LTWP, shown in Figure 7. Theoretical and real data are collected to solve the CVS and DES model, so that, the cutting parameters and process flow can be timely adjusted according to the actual cutting condition. With this idea, two objectives, respectively adaptive controlling for machining quality and adaptive managing for process flow, can be realised for the adaptive machining CPS. It should be noted that, this idea is also suitable for other adaptive machining CPSs, such as adaptive positioning of LTWP, adaptive tool wear compensation, etc. And only controlling machining chatter and thickness error is researched as an example to detail the unified model in section 3.

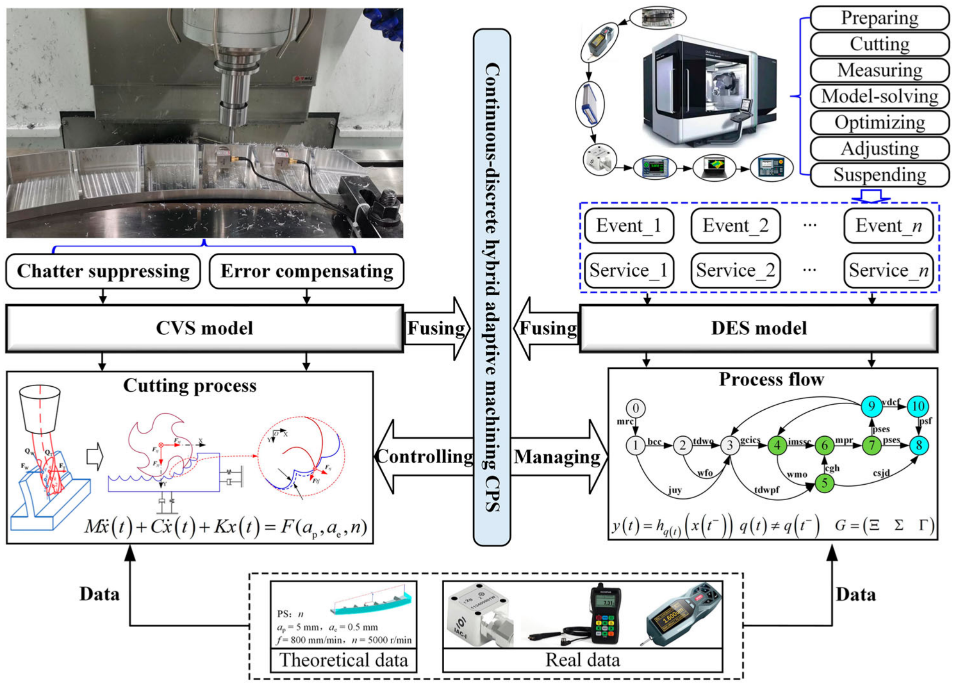

Figure 7. Integration of CVS and DES.

Following the idea of continuous–discrete hybrid CPS building, the FSM, that is a commonly hybrid system modelling method, is employed to construct the unified CPS model, and mathematically expressed as

$$\begin{cases} \dot{x}(t) = \boldsymbol{A}x(t) + \boldsymbol{B}u(t) & q(t) = q(t^-) \\ y(t) = \boldsymbol{C}x(t) + \boldsymbol{D}u(t) & \\ y(t) = h_{q(t)}(x(t^-)) & q(t) \neq q(t^-) \\ G = (\Xi \quad \Sigma \quad \Gamma) & \\ u(t) = \text{Optimizing}(GM^{\text{PS}_i}, PM^{\text{PS}_i}) & \\ x(t) = \begin{bmatrix} x_c(t) \\ x_e(t) \end{bmatrix}, u(t) = \begin{bmatrix} u_c(t) \\ u_e(t) \end{bmatrix} f_{q(t)} = \begin{bmatrix} f_{c,q(t)} \\ f_{e,q(t)} \end{bmatrix} & \\ \boldsymbol{A},\boldsymbol{B},\boldsymbol{C},\boldsymbol{D} = f(GM^{\text{PS}_i}, PM^{\text{PS}_i}) & \end{cases} \tag{13}$$

In which, G represents the DES. $x(t)$ represents CVS. The cutting process and process flow are coupled with each other in adaptive machining CPS, and $x(t)$ is controlled with the running of DES.

Equation (13) is the unified model for continuous–discrete hybrid adaptive machining CPS. In this model, the process flow execution is driven by discrete events, and the continuous variables are adaptively adjusted by services execution in the flow. Thus, the adaptive controlling for machining quality and adaptive managing for process flow can be realised. This model is also the core to drive the running of adaptive machining CPS.

Based on Equation (13), Figure 8 illustrates the FSM model of continuous–discrete hybrid adaptive machining CPS of LTWP. In this figure, the number in a circle represents the specific services, and the word near to arrows is discrete events presented in Appendix 2. Moreover, several key services are illustrated. For example, when service-5 (PS performing) is executing, the event-*pss* (PS started) is generated, and it is used to trigger the execution of service-6 (Vibration data collecting). After that, when PS is finished, events-*psf* (PS finished) and *vdc* (Vibration data collected) are generated, and they trigger the execution of service-8 (Physical model constructing). The execution of other services and events is the same with this algorithm.

Furthermore, this unified model has four functionalities, first, this model details the logical relationship between CVS and DES, as well as services and discrete events, and it is useful for analysing complex adaptive machining CPS. Second, a comprehensive services flow is built to automate the whole machining process execution, and both processes for adaptive machining quality controlling and adaptive process flow managing are modelled. Thirdly, the typical operations are encapsulated as services, which are convenient for management and invocation with the vision of 'software-defined manufacturing'. Finally, the different services can be composited and configured to facilitate the automatic process planning and execution according to different machining requirements, and it is the future trend for the industrial

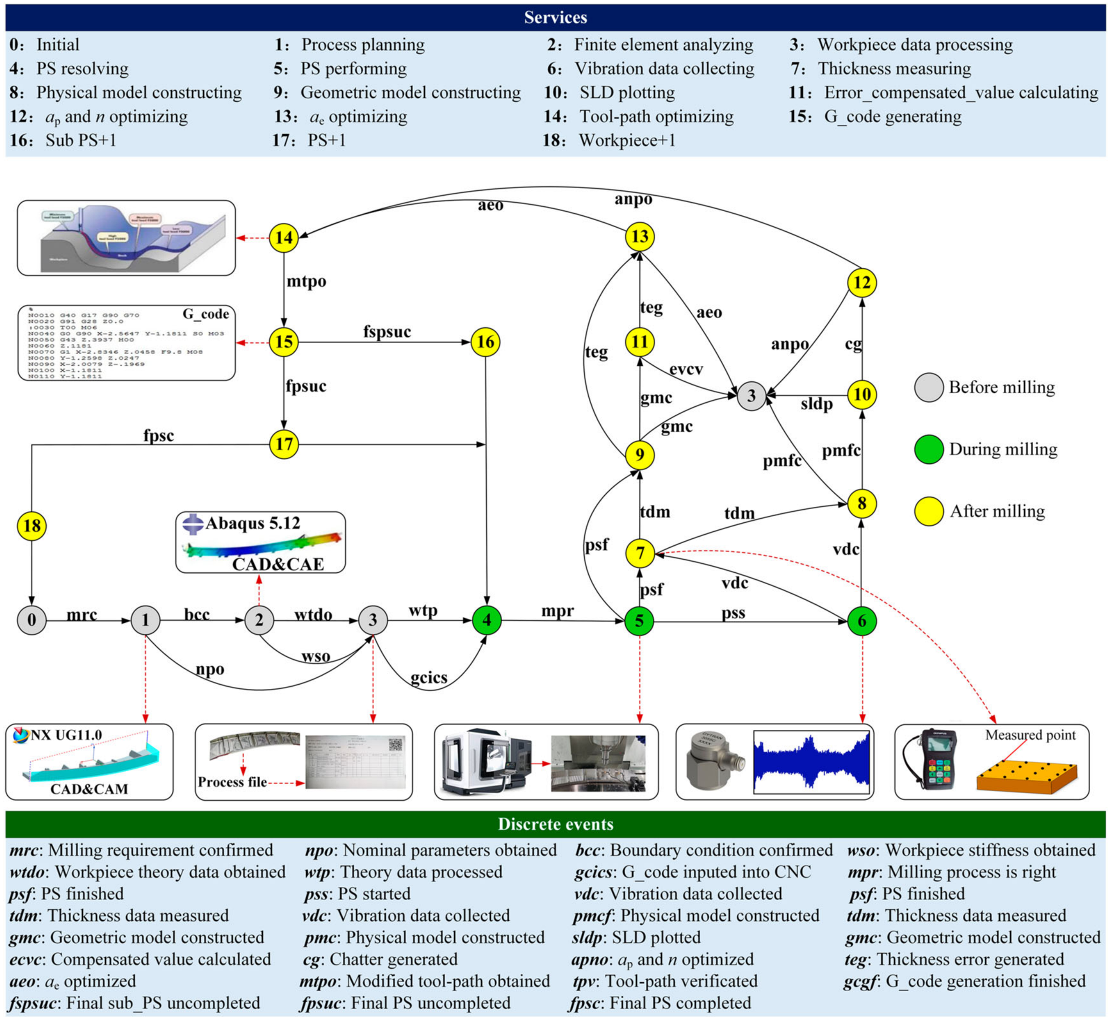

Figure 8. Finite state machine model for adaptive machining CPS.

control and management of complex manufacturing processes.

3.4. Features of the unified model

The above sections detail the unified model for controlling machining chatter and thickness error. Furthermore, this model is also unified for the different workpieces, different machining stages, different machining problems, and different adaptive machining technologies, shown in Figure 9. Generally, three machining stages can be divided, respectively before, during, and after machining, and different machining problems have existed in each stage. For example, low-efficiency positioning of LTWP before machining, difficult-suppressing chatter and insufficiency-compensating thickness error during machining, as well as low-efficiency inspecting after machining. To cope with these problems, adaptive machining technologies are applied, and they run as different CPSs with the algorithm of 'measuring-feedback-optimising-operating'. Thus, adaptive machining CPS is essentially a continuous–discrete hybrid system, and Equation (13) can be used for modelling the adaptive machining CPS for different problems in different stages.

From the above analysing, four features can be concluded for the unified model, respectively universality, integrability, expandability, and reconfigurability, shown in Figure 9, and they are discussed as follows.

Universality. The unified model can be applied to the adaptive machining of LTWP with different geometric shapes (plane-workpiece, curved workpiece, etc.), different materials (aluminium alloys, titanium alloys, etc.), and even different processes (milling, turning, etc.). The adaptive machining for all of these working conditions follows the close-loop of 'measuring-feedback-optimising-machining', and the continuous variables are controlled by the execution of a series of services in the

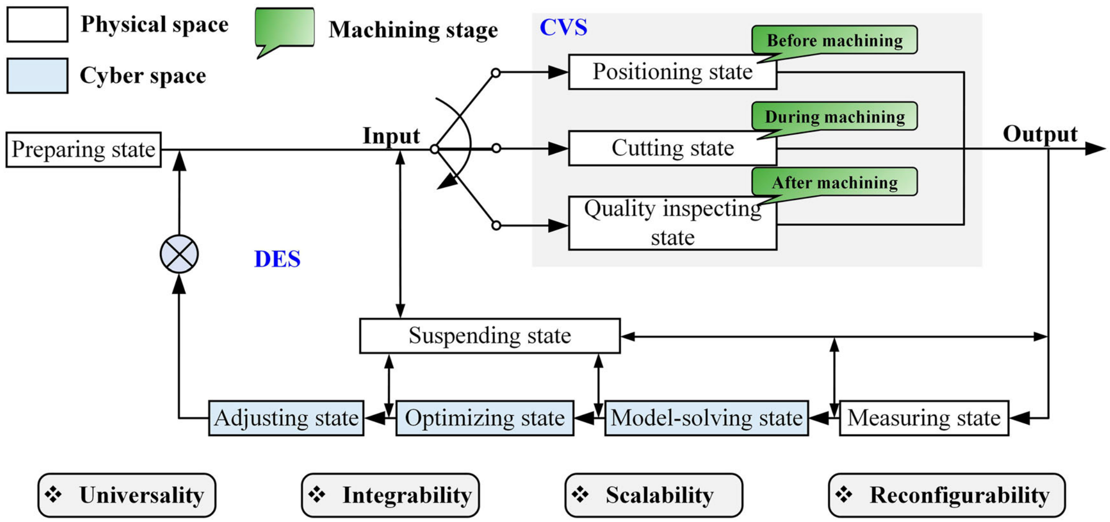

Figure 9. Illustration of the features of the unified model.

loop, so that it can timely track the current cutting condition. Thus, the universality is an obvious feature of the unified model.

Integrability. The unified model integrates the CVS and DES in adaptive machining CPS, and algorithms controlling for machining quality and managing process flow are contained in this model. Hence, the managing and controlling for complex adaptive machining CPS can be realised in this model. Besides, the operations in physical- and cyber-space are interactively executed to solve machining problems in CPS. Thus, the integration of operations in physical- and cyber-space is also modelled by the unified model.

Scalability. The unified model can be applied to other machining technologies by expanding the models of CVS and DES. For example, when modelling the adaptive positioning CPS of LTWP, the actual position of LTWP is defined as continuous variable $x_p(t)$, and the CVS model for this variable can be constructed by the adaptive positioning algorithm with Equation (7). After that, the DES model including posture measuring, posture adjusting value calculating, and posture adjusting, etc., are constructed based on Equation (12). Finally, the unified model for adaptive positioning is obtained as Equation (13), and this model gives the theory support for actual position controlling and positioning process flow managing for CPS. Similarly, other adaptive machining CPSs are modelled in the same way.

Reconfigurability. The unified model detailed the running algorithm of adaptive machining CPS, in which services, that are driven by events and constrained by rules, are executed to control continuous variables. Thus, to realise different machining requirements, the process flow in CPS can be reconfigured by modifying the services, events, and rules. For example, if the chatter-controlling is not needed, the rules for related services and events are shielded from Equation (13). And if new operations/events/rules are required, and it can be defined and integrated into Equation (13). Thereby, the reconfigurability is obviously featured for the unified model.

All in all, the unified model with these four features can provide a useful way for modelling adaptive machining CPS. Furthermore, three innovations can be concluded, (1) The theory of continuous–discrete hybrid system is first introduced to modelling of adaptive machining CPS. This is a more comprehensive and unified model, in which the CVS and DES are integrated and fused. And the actual running process of adaptive machining CPS could be more accurately reflected. (2) The unified model proposed a new approach to model the processes for machining quality controlling and process flow managing. In this model, both the information for adaptive machining technologies and adaptive machining system management are simultaneously considered. (3) The constructed model has four features, respectively universality, integrability, scalability, and reconfigurability. Based on these features, various new and specific CPS models can be quickly formed according to the different requirements.

4. CPS implementation based on the unified model

According to the above unified model, this section is organised to build an adaptive machining CPS for LTWP. After that, the adaptive control for machining quality via solving machining chatter and thickness error are verified based on the CPS.

4.1. CPS built for adaptive machining system

The adaptive machining CPS contained two parts, respectively hardware and software, shown in Figure 10(a). Hardware is used to perform adaptive machining for LTWP, and the software is a module under NX UG 11.0, which is second developed with NX Open C++ based on the unified model built in section 3. To verify the proposed method in this paper, the Hardware and software are first introduced in the following text.

For hardware, machine tool, LTWP, and three kinds of sensors are contained (Figure 10(b)). The machine tool equipped with a cutting tool (φ12 mm, teeth number = 3) is used for cutting, and a Siemens 840D CNC system controls the machine tool to perform planned cutting parameters. The LTWP includes two same parts, respectively Part_1 and Part_2, and they are made of Al–6061 (density is 2.75×10^3 Kg/m^3, Young's modulus is 71 GPa, Poisson's ratio is 0.33). Part_1 is machined with a nominal machining method, the cutting parameters are planned before machining, and stay unchanged during the machining process. Part_2 is machined with adaptive machining CPS, and the cutting parameters are timely adjusted based on time-varying IM of LTWP. Sensors include acceleration sensors (INV9832-50), thickness sensor (Olympus MagnaMike8600), and roughness sensor (INSIZE-ISR-C300). Acceleration sensors collect the in-process machining vibration data for LTWP, and the thickness sensor measures the thickness of LTWP, roughness sensor measures the roughness of LTWP. These data are sent to the adaptive machining software for processing. Among these data, machining vibration data belongs to physical data, that is used to build the PM of LTWP. The thickness and roughness data are used to build the GM of LTWP. After that, the IM of LTWP is obtained based on PM and GM, which is used to optimise cutting parameters.

For software, five modules are contained in this software, respectively Workpiece theory information module 1), Services execution state module 2), Workpiece real information module 3), Process optimisation module 4), and Data storing module 5). And the functions of these modules are detailed as follows. Here, module 5) is only a storing button, and it is not illustrated in Figure 10(c) due to space limit.

1) Workpiece theory information module. This module is mainly used to extract the theoretical workpiece data of the current LTWP, including the nominal geometric and physical data as well as cutting

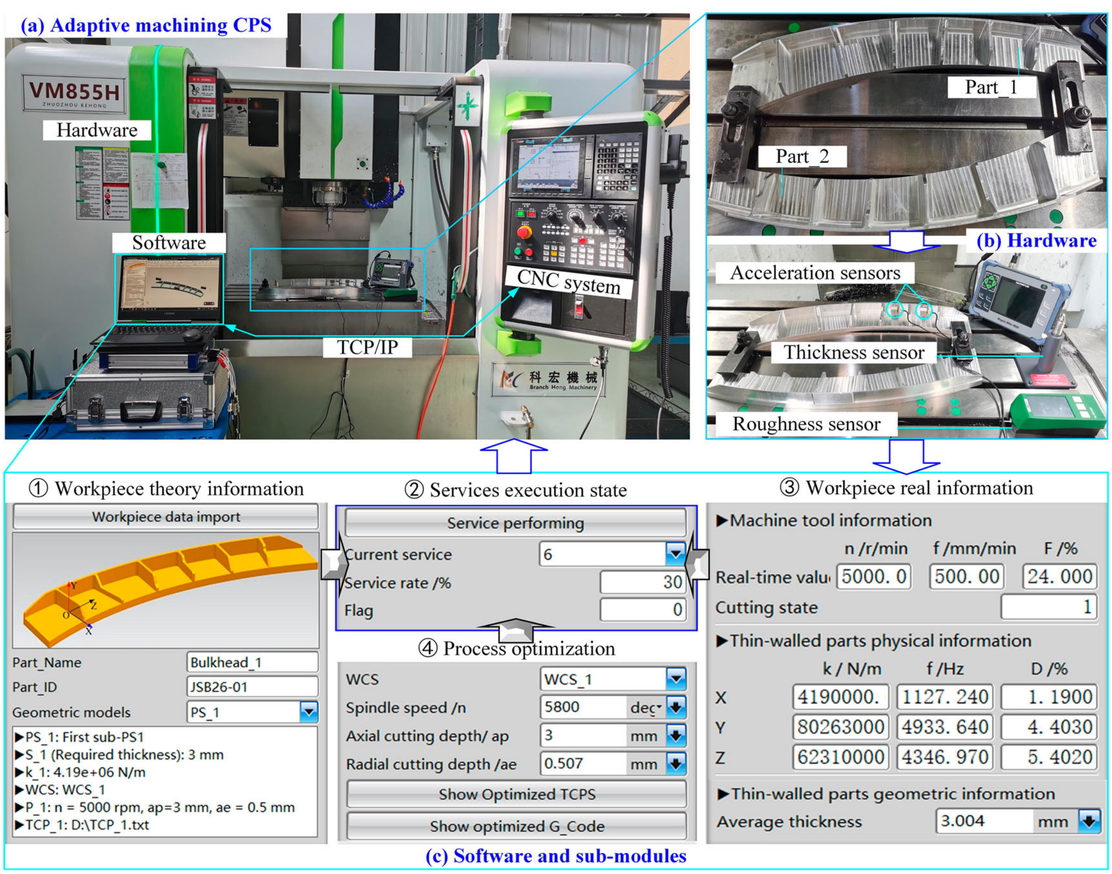

Figure 10. Adaptive machining CPS for experiments.

parameters. These data are obtained before milling based on CAD/CAM/CAE. Note that, the information in this module is obtained by service '1, 2'.

2) Services execution state module. This module is used to display and monitor the current service execution rate, in which, 'Service rate = 100%' means the current service is completed and the '*Service.Flag*' is set as '1' at the same time.

3) Workpiece real information module. This module constructs the time-varying information model for LTWP. The information of LTWP is obtained with the acceleration sensors (service '6') and thickness sensors (service '7'). After data collection, the physical and geometric models for LTWP re constructed (service '8, 9'). These kinds of information provide key feedback for adaptive process optimisation.

4) Process optimisation module. This module is used to optimise the cutting parameters and G_Code based on the information model of LTWP (obtained in module 3)). The optimisation algorithm is detailed in section 2.1 and runs in the background of the software. This module is matched with services '3, 10-17'.

5) Data storing module. After process optimisation, this module mainly stores the optimised cutting parameters and G_Code into a database. If these parameters are used, they can be quickly searched.

The above five modules are respectively related with several services, and the rule engine is used to manage the services execution process in the background of the software. Figure 11 illustrates the services executed algorithm based on the rule engine, and the definitions of services '9, 12' are detailed. For example, the service 9 is firstly packed as ***Class Physical_Modelling*** based on Equation (10). Then, the execution rule for service '9' is defined as ***Rule Physical_Modelling_R*** based on the events-triggering principle (events '*wdc* and *psf*', Equation (11)). Finally, the defined rule with service and events are integrated into the rule engine as ***Switch Flow_State {case Modellinig_Solving_State:}*** (Equation (12)), and this service will be executed based on the defined rule when events are generated. It can be obtained from Figure 11 that, the services and rules are modularised according to the unified model in section 3.2, so that, the process flow can be managed and recomposed according to the different machining requirements via services invocation and rule configuration. This service-executed algorithm is running in the background of the software, and controls the whole adaptive machining CPS.

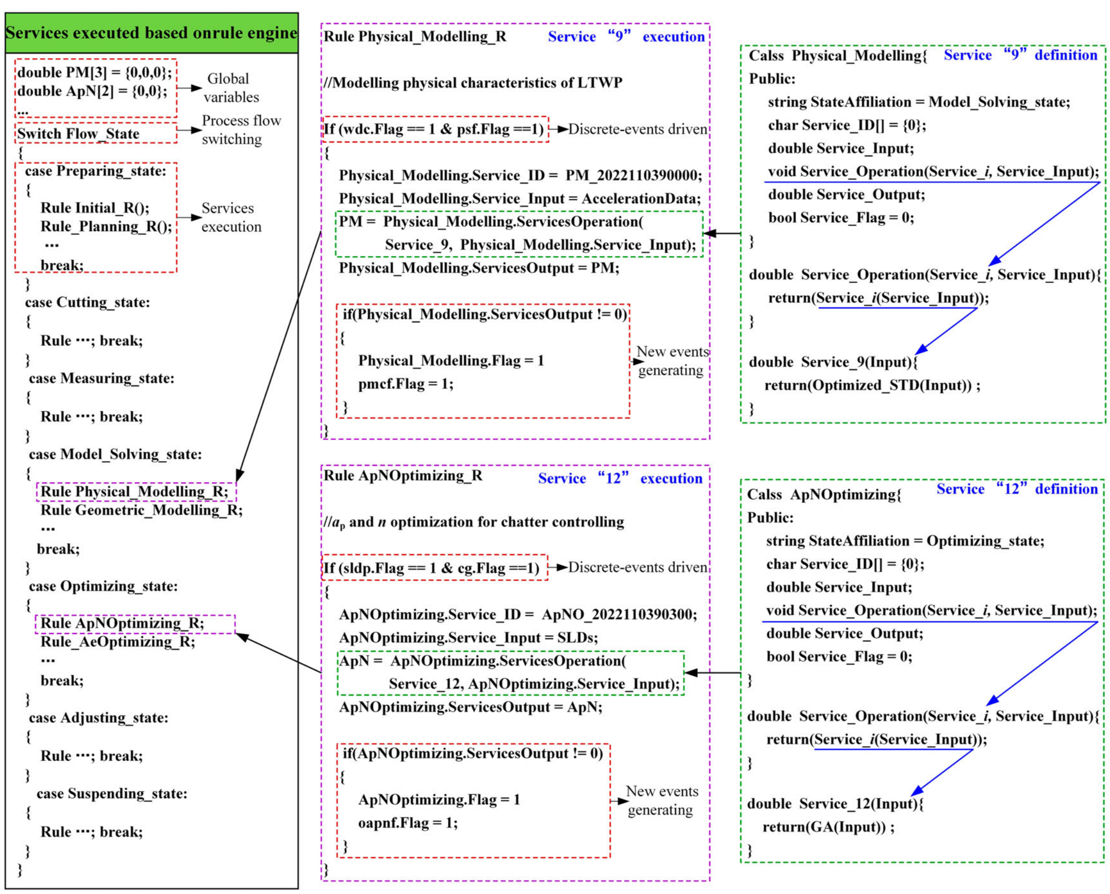

Figure 11. Services executed algorithms based on rule engine.

From the analysing, hardware is mainly mapped to physical space, while the software with the database is cyberspace. The hardware and software are combined to realise the adaptive controlling for machining quality and adaptive managing for process flow.

4.2. Machining result of adaptive machining CPS

Based on the adaptive machining CPS, milling is performed in Part_1 and Part_2. In the preparing state, the theoretical geometric of LTWP is obtained via execution of **services '1'**. The height and initial thickness of the LTWP are 30 and 3.5 mm. And the final thickness reached to 2 mm after machining. Under this requirement, 4 PSs with 30 sub-PSs are planned (One PS is used to remove one-layer material, and one PS is divided into several sub-PSs). Next, the theoretical physical information (Stiffness for each PS and Modal shape for each sub-PS) of LTWP for each sub-PS is calculated. Then, the theoretical geometric and physical information are stored in the database via **service '3'**. Table 1 lists the planned cutting parameters and stiffness for LTWP.

After that, the process flow is transferred to the cutting state and measuring state. Part_1 and Part_2 are respectively milled using the planned parameters and adaptive machining CPS (**services '4, 5'**). During milling, machining vibration data are collected by **services '6'.** And after PS_i performing, the real thickness is measured with **service '7'**.

When data collection is finished, the process flow is moved to the model-solving state and optimising state. In the model-solving state, **services '8, 9'** are executed to construct IM (*GM* & *PM*) for LTWP. And **services '10, 11'** are used to obtain the SLD and error compensated value. In the optimising state, the **services '12, 13, 14'** are executed to optimise the cutting parameters.

After optimisation, the flow reached to adjusting state. A new G_Code (**service '15'**) for the next sub-PS or PS is generated based on optimised cutting parameters. And the new G_Code is sent into CNC system. The chatter and thickness error can be controlled when the optimised G_code (**service '16, 17'**). It should be noted that the chatter is controlled for each sub-PS_i, and the thickness error was compensated for each PS_i. Following these steps, the below text details machining results of chatter controlling and error compensating.

Result 1 Chatter controlling (Services '4, 5, 6, 8, 10, 12, 14, 15, 16, 18').

Machining chatter is controlled for each sub-PS_i. Due to the space limit, only the machining result of the first sub_PS_1 and the second sub_PS_1 is given, shown in Figure 12. When the first sub-PS_1 of Part_2 is performed, the machining vibration data are collected (Services '5, 6'). Then, the modal parameters ($\omega^{1^{\text{st}}\text{sub-PS}_1}, \xi^{1^{\text{st}}\text{sub-PS}_1}$) in directions of X, Y, and Z are estimated using the method in Zhao, Zheng, and Yu (2022). So that, the $\text{FRF}^{1^{\text{st}}\text{sub-PS}_1}$ of LTWP are calculated with the modal shape and modal parameters, and the $\text{PM}^{1^{\text{st}}\text{sub-PS}_1}$ is constructed. Based on $\text{PM}^{1^{\text{st}}\text{sub-PS}_1}$, the SLD is calculated, shown as the blue line in Figure 12 (Services '8, 10').

Obviously, machining chatter occurred in the first sub-PS_1 under planned parameters $n^{1^{\text{st}}\text{sub-PS}_1} = 5000$ rpm, $a_p^{1^{\text{st}}\text{sub-PS}_1} = 3$ mm, and the chatter frequency (CF) is 1197.51 Hz. Hence, to control machining chatter, the cutting parameters of the second sub-PS_1 are optimised as $n^{2^{\text{nd}}\text{sub-PS}_1} = 5800$ rpm, $a_p^{2^{\text{nd}}\text{sub-PS}_1} = 3$ mm. When the second sub-PS_1 is performed with the optimised cutting parameters, the chatter is controlled, and the main frequency is the spindle frequency (SF) (Services '12, 14, 15'). The following sub-PS_i is performed in the same way, and the SLDs for 1st sub-$PS_{(1-4)}$ are illustrated as different colours in Figure 12. The 3D-SLD can be obtained with these SLDs, which can be used to optimise cutting parameters for the next LTWP. It should be noted that, only SLD for each sub-PS is used to optimise cutting parameters in this experiment, and the 3D-SLD is not calculated for each sub-PS, because the test workpiece is not large enough. If the workpiece is large, and the varying-FRF for sub-PS should be considered, the proposed chatter controlling method (Zhao, Zheng, and Yu 2022) is also suitable.

Result 2 Error compensation (Services '4, 5, 7, 9, 11, 13, 14, 15,17, 18').

Thickness error is compensated for each PS_i, shown in Figure 13. When PS_1 is finished, the real thickness

Table 1. Theoretical geometric and physical data obtained by service '1, 2'. 'R' means Rough, 'S' means semi-finishing, 'F' means finishing.

Part index	PSs: Theoretical cutting parameters	PSs: Sub-PS_i	Operation	Stiffness (N/mm, Y direction)
Part_1	$PS_1\{n = 5000$ rpm, $a_p = 3$ mm, $a_e = 0.5$ mm, $f_z = 0.02$ mm/tooth$\}$	10	R	4.19×10^6
	$PS_2\{n = 5000$ rpm, $a_p = 3$ mm, $a_e = 0.5$ mm, $f_z = 0.02$ mm/tooth$\}$	10	R	2.91×10^6
	$PS_3\{n = 5000$ rpm, $a_p = 6$ mm, $a_e = 0.25$ mm, $f_z = 0.02$ mm/tooth$\}$	5	S	2.17×10^6
	$PS_4\{n = 5000$ rpm, $a_p = 6$ mm, $a_e = 0.25$ mm, $f_z = 0.02$ mm/tooth$\}$	5	F	1.88×10^6
Part_2	1st sub-$PS_1\{n = 5000$ rpm, $a_p = 3$ mm, $a_e = 0.5$ mm, $f_z = 0.02$ mm/tooth$\}$	1	R	–
	2nd sub-PS_1- PS_n {Adaptive machining}	n-1	F	

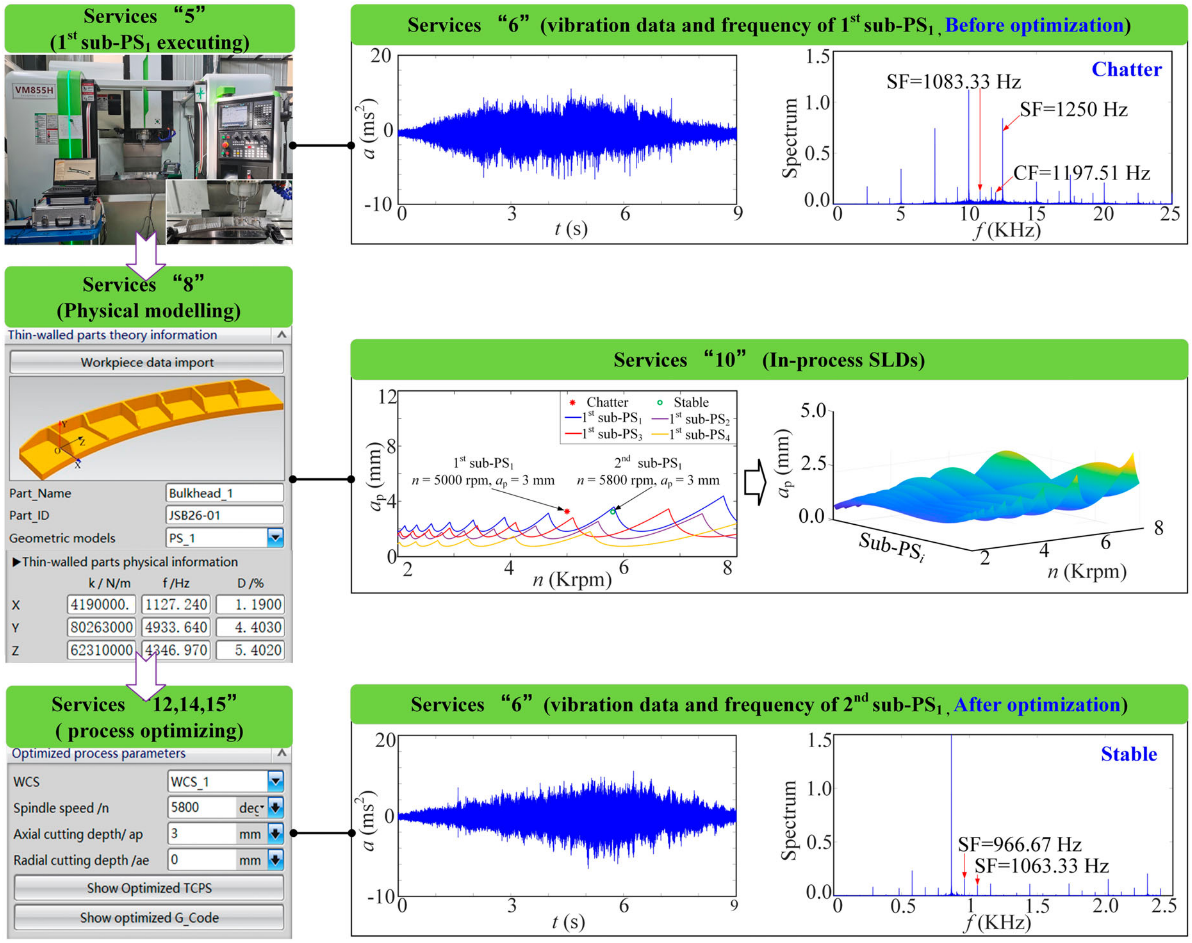

Figure 12. SLD calculating and machining chatter controlling for part_2.

at 18 key points on Parts_1 and Part_2 are measured with a thickness sensor, and the real thickness value and thickness error are shown in Figure 12 (Services '5, 7'). The thickness error of Part_2 is 0.004 mm, so the error compensation value is calculated as 0.007 mm (Services '9, 11'), using the method in reference of Zhao, Zheng, and Zhang (2021). After that, the TCPs (represent as radial cutting depth for this workpiece) of PS_2 is optimised $a_e^{PS_2} = 0.5 + 0.007 = 0.507\text{mm}$. And the optimised TCPs is performed in PS_2 for the thickness error compensation (Services '13, 14, 15'). After PS_2, real thicknesses are measured for parts_1 and_2, and the real thickness ranges of parts_1 and_2 are respectively (+2.503 ∼ +2.519 mm) and (+2.501 ∼ +2.513 mm). It can be obtained that the thickness error of Part_2 is significantly compensated via the adaptive machining CPS, and the machining precision is improved for LTWP.

Finally, Figure 14(a) shows the final surface roughness for Part_1 and Part_2. And Figure 14(b) shows the in-process real thickness for Part_1 and Part_2. It can be obtained that, the LTWP milled with adaptive machining CPS has higher machining surface quality and thickness accuracy. According to the machining results of LTWP, three conclusions are concluded:

(1) Adaptive machining CPS reduces the machining surface roughness for LTWP, and the surface roughness of parts_1 and_2 are, respectively, Ra 2.4 and Ra 1.6, as shown in Figure 14(a).
(2) Adaptive machining CPS can significantly compensate thickness error for LTWP. The maximum thickness error of parts _1 and _2 after PS_4 are 0.028 and 0.015 mm (Figure 14(b)), respectively. Thus, the adaptive machining CPS reduced thickness error by 46.42%. Furthermore, the error compensation effect is improved with the stiffness decreasing, as shown in Figure 14(b).
(3) Adaptive machining CPS can be reconfigured according to different machining requirements via process flow management. For example, when chatter controlling is not needed, the rule engine can shield the services, events and rules about chatter controlling.

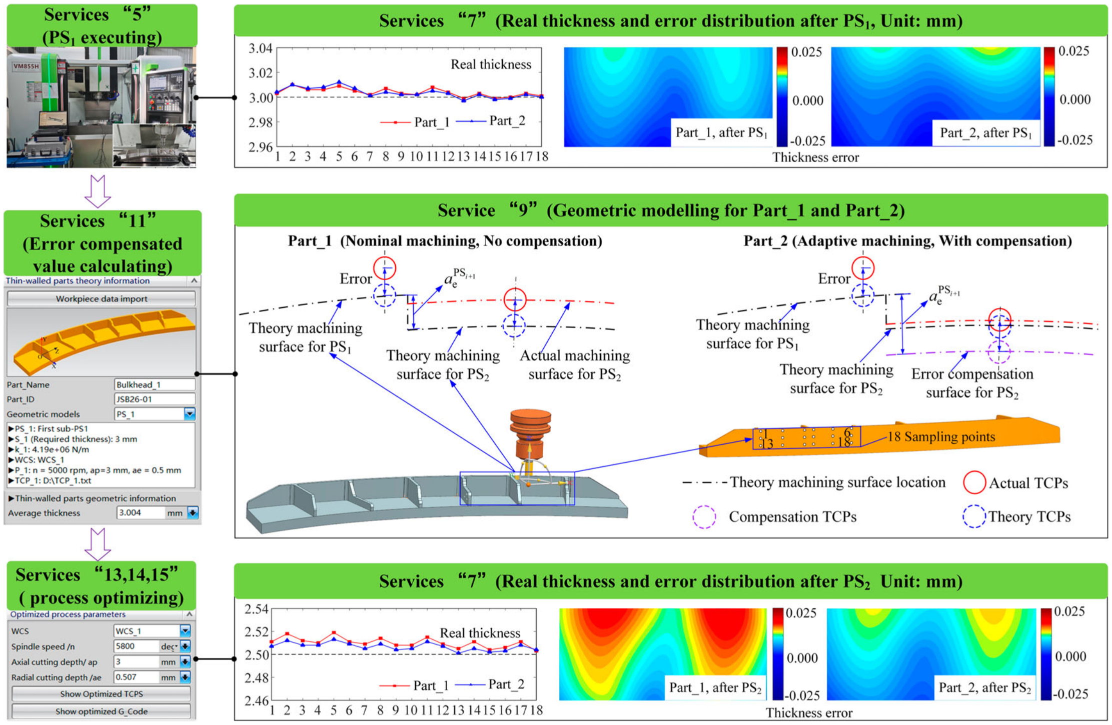

Figure 13. Error compensation result for the first two PSs of part_1 and part_2.

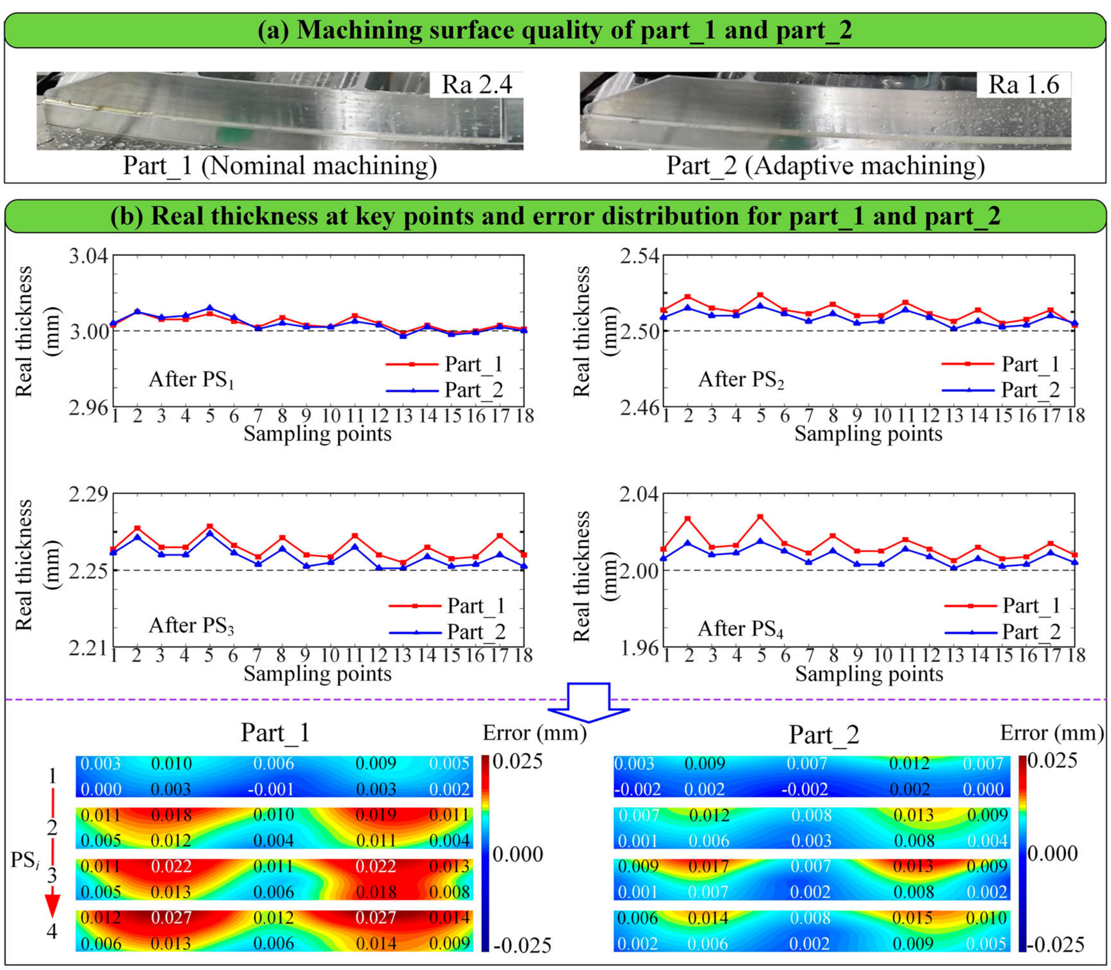

Figure 14. Machining result comparison for Part_1 and Part_2.

5. Conclusions

To realise adaptive controlling of machining quality and adaptive management of process flow, a unified model for adaptive machining CPS of LTWP is proposed and constructed. The adaptive machining CPS is regarded as a continuous–discrete hybrid system, so the model of CVS and DES for CPS is built. After that, the unified model is fused by integrating the models of CVS and DES. Based on the research results presented in this paper, three conclusions are as follows:

(1) The unified model provides a new idea for modelling adaptive machining CPS, which reveals the integration mechanism of cutting process (CVS) and process flow (DES). The algorithm of controlling and management for adaptive machining CPS is formed based on the unified model.
(2) The unified model is a comprehensive modelling tool, which has four features, namely universality, integrability, scalability, and reconfigurability. Through these four features, the model of other adaptive machining CPSs can be quickly constructed and reconfigured according to the various machining requirement. This is very useful for small batch customised production of LTWP.
(3) The unified model can provide an algorithm basic for controlling and managing system development of adaptive machining CPS. This is also validated in this paper, and experiment results show that it not only can efficiently control machining quality, but also orderly manage the process flow.

Actually, this is the first time to construct a unified model for adaptive machining CPS by integrating CVS and DES. Thus, a series of problems are also generated and needed to be solved in the future. Firstly, it is a worthwhile work to model CVS with real-time feedback and optimisation. Secondly, how to deal with the human-operations in adaptive machining CPS must be considered. Thirdly, the model application should be expanded and transferred to other issues of adaptive CPSs, such as the adaptive positioning system of LTWP. Fourthly how to apply the model to digital twin-based adaptive machining is another interesting and exciting work.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendices

Appendix 1. Services encapsulated for adaptive machining CPS

Flow state	Service	Services model
Preparing state	0	*Initial Preparing, ID, -, 0 -, 0/1*
	1	*Planning Preparing, ID, ProcessFile, 1, Geometric_Inf, 0/1*
	2	*FEA Preparing, ID, GeometricModel, 2, Stiffness, 0/1*
	3	*DataStoring Preparing, ID, Geometric_Inf&Stiffness, 3, -, 0/1*
Cutting state	4	*Resolving Cutting, ID, ProcessFile, 4, G_Code, 0/1*
	5	PS(*i,i*)_Execution *Cutting, ID, G_Code, 6, MachiningResult, 0/1*
Measuring state	6	*Acceleration_Collecting Measuring, ID, -, 7, AccelerationData, 0/1*
	7	*Thickness_Collecting Measuring, ID, -, 8, ThicknessData, 0/1*
Model-solving state	8	*Physical_Modelling Calculating, ID, AccelerationData, 9, PhysicalModel, 0/1*
	9	*Geometric_Modelling Calculating, ID, ThicknessData, 10, GeometricModel, 0/1*
	10	*SLD_Plotting Calculating, ID, PhysicalModel, 11, SLD, 0/1*
	11	*Error_Compensation Calculating, ID, P&G_model, 12, ErrorComValue, 0/1*
Optimising state	12	*ApNOptimizing Optimizing, ID, P_Model, 13,* a_p *& n, 0/1*
	13	*AeOptimizing Optimizing, ID, P_Model, 14,* a_e*, 0/1*
	14	*ToolpathOptimizing Optimizing, ID,* a_p *&*a_e*, 15, Toolpath, 0/1*
Adjusting state	15	*G_CodeGeneration Adjusting, ID,* a_p *&*a_e *& n, 16, G_Code, 0/1*
Suspending state	16	*PS_Plus Pause, ID, -, 17, Next_PS, 0/1*
	17	Workpiece*_Plus Pause, ID, -, 18, Next_Workpiece, 0/1*

'-'in the services means that this parameter is not needed

Appendix 2. Services and discrete events list

Flow state	Service	Operation	Related events
Preparing state	0	Initial	–
	1	Process planning (CAM)	*mrc*: Milling requirement confirmed *npo*: Nominal parameters obtained
	2	Finite element analysing (CAE)	*bcc*: Boundary condition confirmed *wso*: Workpiece stiffness obtained
	3	Workpiece data processing	*wtdo*: Workpiece theory data obtained *wtp*: Theory data processed
Cutting state	4	PS resolving	*gcics*: G_code inputed into CNC
	5	PS performing	*mpr*: Milling process is right *psf*: PS finished
Measuring state	6	Vibration data collecting	*pss*: PS started *vdc*: Vibration data collected
	7	Thickness measuring	*psf*: PS finished *tdm*: Thickness data measured
Model-solving state	8	Physical model Constructing	*vdc*: Vibration data collected *pmcf*: Physical model constructed
	9	Geometric model Constructing	*tdm*: Thickness data measured *gmc*: Geometric model constructed
	10	SLD plotting	*pmc*: Physical model constructed *sldp*: SLD plotted
	11	Error compensated value calculating	*gmc*: Geometric model constructed *ecvc*: Compensated value calculated
Optimising state	12	a_p, *n* optimising (Chatter suppressing)	*cg*: Chatter generated *apno*: a_p and *n* optimised
	13	a_e optimising (Error compensating)	*teg*: Thickness error generated *aeo*: a_e optimised
	14	Tool-path optimising	*mtpo*: Modified tool-path obtained
Adjusting state	15	G_code generating	*tpv*: Tool-path verificated *gcgf*: G_code generation finished
Suspending state	16	Sub_PS+1	*fspsuc*: Final sub_PS uncompleted
	17	PS+1	*fpsuc*: Final PS uncompleted
	18	Workpiece+1	*fpsc*: Final PS completed