A CYBER-PHYSICAL MACHINE TOOL FRAMEWORK BASED ON STEP-NC

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ABSTRACT

Cyber-Physical Machine Tool (CPMT) is one of the main concepts that has emerged with the rise of Industry 4.0 and Machine Tool 4.0. It integrates the physical machine tool and machining processes with computation and networking by creating a Machine Tool Digital Twin (MTDT). Standard for the Exchange of Product data compliant Numerical Control (STEP-NC) defines a machine independent bi-directional data standard for Computer Numerical Control (CNC) systems. It is capable of transferring richer information compared to conventional G-codes. All machine tools in the manufacturing field have physical variances between each other which affect the final machining quality. At present, physical variances between machines are manually compensated by human experiences which is not a consistent method. In this paper, we propose an intelligent CPMT framework for machining parameter optimization based on STEP-NC data model with the capability of taking the physical variances between machine tools into account. This framework correlates real-time physical and numerical data of the machine tool with the rich machining information contained in the STEP-NC model to establish a sustainable machining knowledge base. Established machining knowledge base is utilized for both offline and real-time machining parameter optimizations inside the framework.

Keywords: Cyber-Physical Machine Tool (CPMT), Cyber-Physical System (CPS), Smart Manufacturing, STEP NC, OPC UA

1 INTRODUCTION

With industry 4.0 rapidly emerging into the manufacturing field, there is a significant increase in the amount of available data throughout the entire manufacturing process. Cyber-Physical Systems (CPS) with its digital twin (DT) or cyber-twin is one of the key concepts emerging along alongside industry 4.0 [1]. CPS creates a DT of a physical product or system within the cyberspace while establishing a direct link between the two domains. The link between the two domains allows the DT to reflect every state change that occurs on the physical object. In reverse, the DT link can be bidirectional as state changes on the DT can be reflected onto the physical machine tool through its control systems [2]. For Computer Numerical Controlled (CNC) machine tools, the concept of new generation of Machine Tool 4.0 also emerges, not only representing machining state on the cyberspace but also offers value-added services [3].

One of the aspects of industry 4.0 is global manufacturing by utilizing the modern cybernetic technologies. In modern manufacturing industry, many companies and organizations rely on outsourcing of their product parts where the suppliers can be located in other countries. However, quality assurance becomes very challenging when parts are manufactured in different locations across the globe since there will be a significant amount of variance across manufacturers. Manufacturing of parts demanding high tolerance and finish quality requires fine adjustment of machining parameters based on the machinist experience and understanding of the machining environment. The knowledge gained through the experience of a person cannot be shared easily throughout the organization for future references.

G-code is a standard programming language, ISO 6983 [4], used to define CNC machine tool motions proposed in the 1950's. However, it is still the current de facto standard used within the manufacturing industry. G-code is composed from a series of commands on how to move the machine to make the desired part, but the structure of these commands will vary across machines. Each CNC machine has its own specific motion controlling unit which is only capable of interpreting G-code in a certain format. Therefore a postprocessor is required to translate standard G-code into an appropriate format which is interpretable to a specific motion controller. This G-code's non-structured nature makes it very difficult to correlate any physical data with it to form a knowledge base.

STEP-NC Application Protocol (AP) 238 [5] is an alternative machine control language to G-codes which describes "What" to machine rather than "How" to machine. STEP-NC file provides a structured data format which defines all of the information required to carry out the machining processes. As STEP-NC defines "What" to machine, the CNC motion controller is responsible for interpreting the input file to calculate the machining motions. Therefore, the same STEP-NC file can be executed on different CNC machine with different controllers, making STEP-NC language suitable to form a knowledge base due to its machine-independent nature. The structured data provided by the STEP-NC allows logical correlation with the physical data.

A considerable amount of research has been conducted on machining parameter optimization and physical machine condition monitoring by using various methods. However, most of the researches establish their baseline on theoretical values without incorporating the machine variant data. Physical characteristics of a machine will change over its lifetime depending on the type of machining process it has carried out. These slow time-variant changes of the machine tool physical characteristics are not often noticeable, but it will affect the machining quality over its lifetime. The advantage of the DT over conventional methodologies is the level of interaction that occurs between the DT and its physical counterpart. Detailed analysis of the physical machine behaviour reflected onto the DT will reveal and detect these slow varying machine characteristics, allowing machine tools to automatically make changes to the input machining parameters to preserve or improve the final machining quality.

The framework proposed in this paper utilizes the concept of CPS and DT utilizing structured data of STEP-NC to form a knowledge base. This knowledge base serves a similar purpose to an experienced machinist, enabling connecting applications or algorithms to extract the required information and optimize the input machining parameter for a specific machine. Data from the knowledge base can also be utilized for real-time abnormality monitoring during machining operations. This framework is intended to be ubiquitous to allow access from different locations through the Internet.

The rest of the paper is organized as follows. Section 2 briefly reviews the related research work on Cyber-Physical Machine Tools and STEP-NC based optimization. Section 3 introduces the system architecture of this framework including details explanation of the data flow. Section 4 demonstrates the implementation of this framework through a case study. Finally, Section 5 summarizes the paper and indicates the further work.

2 RELATED WORK

2.1 Cyber-Physical Machine Tools concept

The concept of CPS was firstly introduced in 2006 [6]. CPS marries the physical object in the physical world with its computational capabilities in the cyber-space through bidirectional communication [7]. The communication enables data related activities of the physical equipment to be captured and analyzed in its DT. Thus, valuable information from the data can be extracted and used to predict and find optimized parameters. Likewise, the optimized parameters that can be transferred back to the equipment via a control feedback function. This concept is adopted into the manufacturing domain to monitor shop floor activities and to optimize the entire value chain [8]. To be more precise, the term Cyber-Physical Production Systems (CPPS) has also been introduced [9][10]. Subsequently, diverse applications of CPS have been proposed, such as cyber-physical assembly systems [11], cyber-physical systems for maintenance [12], cyber-physical process monitoring systems [13] and cyber-physical machine tools [14].

Cyber-Physical Machine Tool (CPMT) is defined as a complete CPS-based machine tool that is smarter, well-connected, widely accessible, more adaptive and more autonomous [15]. CPMT architecture consists of three main components, i.e. physical machine tools, communication networks, and Machine Tool Digital Twin (MTDT). The difference between a traditional machine tool and a CPMT lies within the existence of its MTDT that functions as the external brain of the machine tool where it can take full advantage of the incoming real-time data. Currently, all the CPMT systems are focused on optimizing machine tool parameters through physical condition monitoring. However, up to this point, any actual geometrical information such as machining feature and workpiece is still disregarded from the optimization process.

2.2 STEP-NC based optimization

STEP-NC AP238 is an alternative CNC programming language to G-codes which is developed on the base of a STEP data format under the ISO14649 standard [16]. STEP-NC delivers significantly richer information through to both CNC controller and its operators, enabling them to understand “What” is being machined opposing to “How” it is machined on the G-code.

The characteristics of STEP NC have been extensively investigated for machining parameter optimization purposes. Ridwan et al. [17] proposed a framework for machining parameter optimization using the STEP-NC data and analysing the machining data obtained during the process execution. The system consists of a process control module, knowledge-based evaluation module, and an optimization module. Feedrate and finishing operation were taking as parameters to be optimized where the optimization data was developed under EXPRESS schema [18]. Zhao et al. [19] presented a closed-loop machining for on-line inspection process based on STEP-NC data. A new version of STEP-NC Interpreter was developed. This is one of the early on-machine inspection systems where both workpiece and tool are inspected. Danjou et al. [20] presented the manufacturing knowledge management based on STEP-NC that is able to assist part designers to apply optimal machining condition during the design phase. Wosnik et al. [21] proposed a STEP-NC enabled feedback loop to the manufacturing process by incorporating a mathematical observer to calculate the cutting forces from motor currents.

Although research on optimizing machine tool parameters has been extensively studied, many of them focused on offline process planning and optimization. While some work proposed on-line monitoring functions, data processing and analytics were not included. The extracted STEP-NC process data and real-time machining data have not been correlated in a structured format. Consequently, it is difficult to understand "What" is happening during machining of a feature.

2.3 Research Gaps

Extensive studies on machining parameter optimization based on STEP-NC have been investigated. However, only a few of them associate the real-time physical data obtained from the physical machine tool to the actual machining data. The rich information of STEP-NC and physical machine behaviours are analysed as separate entities. Hence, there are no direct relationships realized between the machining feature and the machine tool behaviours. Optimal machining parameters are often calculated from mathematical models which do not include the physical variance between each machine tool. The framework proposed in this paper aims to bridge this research gap by integrating the information in STEP-NC files with the real-time machining data provided by the DT.

3 SYSTEM ARCHITECTURE

A CPS typically includes a physical layer and a virtual layer. In this paper, we develop a Machine Tool Digital Twin (MTDT) in the virtual layer utilizing OPC Unified Architecture (OPC-UA) information modelling [22]. Figure 1 shows the overall architecture of the proposed framework. To analyse data, machine learning algorithms are embedded which connect to two main function loops, i.e. machining parameter optimization based on previous machining data, and abnormality monitoring loop which monitors real-time machine behaviour.

The MTDT receives real-time machining data from the CNC machine tool along with the executing workingstep data extracted from the input STEP-NC file. All parameters of the MTDT are recorded in a Relational Model Database (RMDB) such as Microsoft (MS) SQL Server in a structured manner. The MTDT parameters are stored under a single data object within the SQL Server model. This data object has a structure similar to the MTDT to correlate all parameters. A data object is created for each STEP-NC workingstep that is executed as a motion on the machine to enable correlation of the physical machine condition with the input machining feature geometry and operation data. The data objects will then be used as the input to the machine learning algorithms where the underlying feature patterns within the data are extracted. Extracted feature patterns are stored back in the SQL server which will form the core of the knowledge base. These extracted feature patterns are used as references to analyze the characteristics of future inputs.

Machining parameter optimization loop is responsible for the observation of the input machining information, i.e. features and operations. When the CNC interface executes a workingstep from the input STEP-NC data, its feature and operation data is uploaded to the MTDT in the OPC UA server before any motion is executed on the machine. Workingstep feature and operation data is compared to past machining data executed on the machine by the machining parameter optimization algorithm. This algorithm gets input data from the machine learning algorithm which extracts the characteristics of the input machining data. From all the inputs, the machine parameter optimization algorithm will alter the input machining parameters where needed, including both feature geometry and machining parameters. The optimized machining data will be fed back into the CNC interface for its execution on the machine which is also able to save the optimized STEP-NC data.

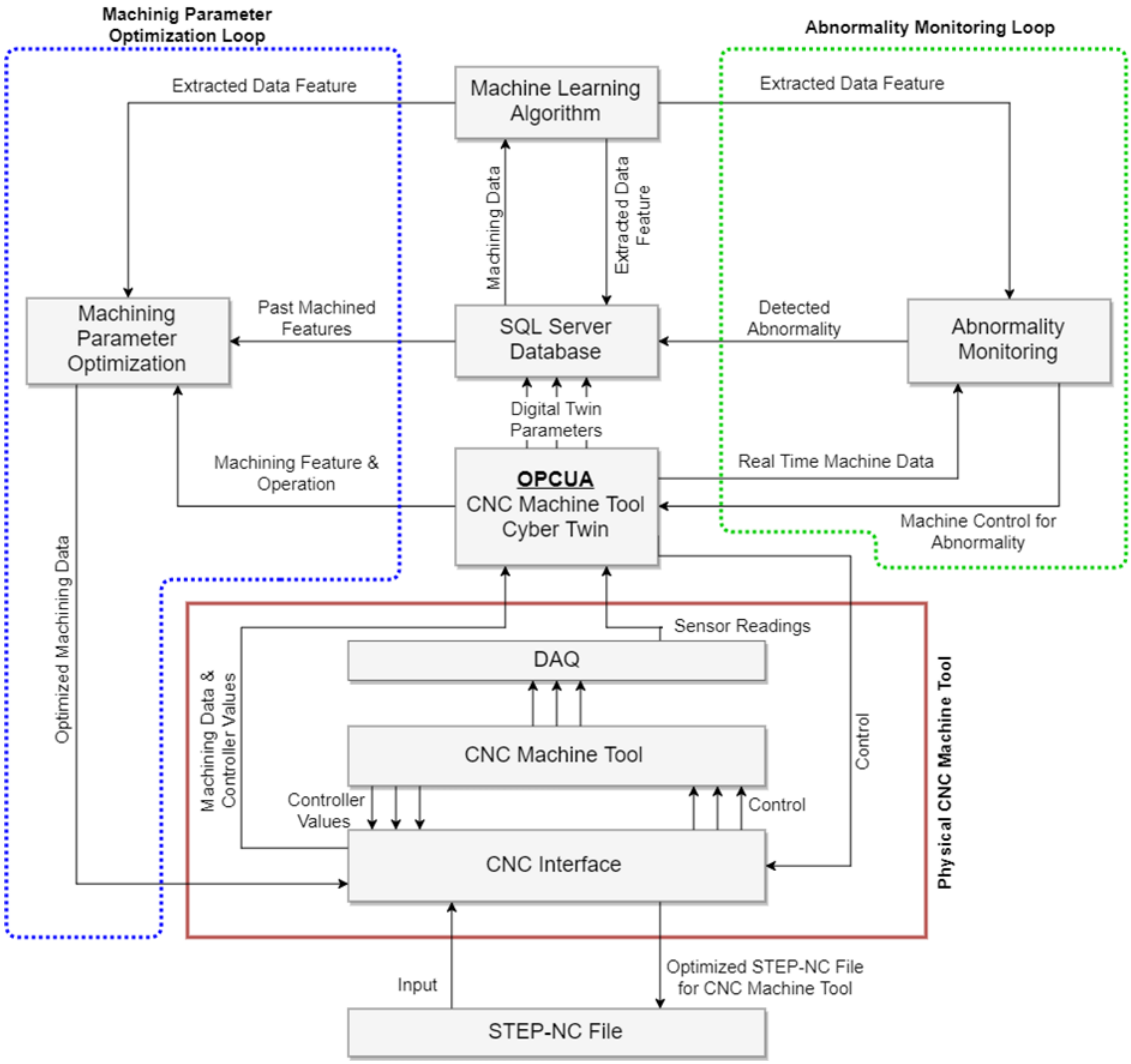

Figure 1: Overall Architecture of Proposed Framework

Abnormality monitoring loop is responsible for monitoring the real-time incoming data from the physical machine tool. Real-time machine data is fed into the abnormality monitoring algorithm where it will be observed for any abnormal behaviour of the physical machine tool during its operation. This algorithm will take the extracted data feature from the machine learning algorithm for the reference of abnormality. If any abnormality is detected during the machining operation, the type of abnormality and its occurrence will be stored within the SQL server as well as machine control for the compensation for the detected abnormality. As OPC UA allows for bidirectional data flow, the compensation control signal can take effect directly through the MTDT in real time.

3.1 CNC Interface

STEP-NC files are loaded into the CNC interface first where it will get parsed into its tree-structured data form. Each node in this tree-structured data is an entity of STEP-NC carrying valuable information. A single STEP-NC file is defined as a “Project” which contains multiple entities underneath it, including Its_id, Main_Workplan, Its_workpieces, Its_owner, Its_release and Its_status. Likewise, each of these entities has multiple entities beneath it, forming the tree data structure. Tree data structure can clearly define the relationships between each entity as every entity must be a child of another entity. The machine executable entity in the STEP-NC file is defined by a “Workingstep” that is an entity encapsulating all information required to machine the defined machining feature, i.e. feature geometry, machining operation parameters, tools, strategies and workpiece setups. An entity which collects a series of Workingsteps is defined as a “Workplan”.

The CNC interface is an OPC UA client that serves as an interface for both CNC and MTDT in the OPC UA server. Numerical parameters obtained from the CNC controller will be reflected in the MTDT through this interface in real time. As OPC UA is capable of bidirectional communication, control commands through the MTDT from another client can be executed on the physical CNC machine.

3.2 Conversion of STEP-NC to XML format

The parsed STEP-NC data in the CNC interface needs to be converted into an appropriate format to carry the contained information through the OPC UA server while preserving its structural integrity. ISO10303-28 standard [23] defines a format of how STEP-NC file can be represented as an eXtensive Markup Language (XML) format as this format is capable of handling information with a parent/child relationship, similar to a STEP-NC tree data structure. XML is a very common data format used in data exchange which can be easily interpolated by humans, making it simple to make alterations. Extensive research has been done on XML data formats thus many reliable software and algorithms are available for various operations on the XML format. An example of a STEP-NC file and its corresponding XML format after conversion is illustrated in Figure 2.

```
ISO-10303-21;
HEADER;
/* Generated by software containing ST-Developer
 * from STEP Tools, Inc. (www.steptools.com)
 */
FILE_DESCRIPTION(('EXAMPLE 2'),'1');
FILE_NAME('EXAMPLE1.STP','2004-5-4T16-32-8',('AUTHOR'),(''),
'WZL ISO10303-PART21 PARSER PACKAGE','','');
FILE_SCHEMA(('MACHINING_MILLING_SCHEMA'));
ENDSEC;

DATA;
#1=CARTESIAN_POINT('LOCATION',(0.,0.,35.));
#2=DIRECTION('AXIS',(0.,0.,1.));
#3=DIRECTION('REF-DIR',(1.,0.,0.));
#4=AXIS2_PLACEMENT_3D('',#1,#2,#3);
#5=PLANE('SECPLANE OF PLANAR FACE: STEP',#4);
#6=PROPERTY_PARAMETER('');
#7=MATERIAL('','',(#6));
#8=CARTESIAN_POINT('',(-2.5,-2.5,-2.5));
#9=DIRECTION('',(0.,0.,1.));
#10=DIRECTION('',(1.,0.,0.));
#11=AXIS2_PLACEMENT_3D('',#8,#9,#10);
#12=BLOCK('BOUNDING BOX OF STOCK',#11,180.,118.9,35.);
#13=WORKPIECE('STOCK',#7,$,$,$,#12,());
#14=CARTESIAN_POINT('',(0.,0.,0.));
#15=DIRECTION('',(0.,0.,1.));
#16=DIRECTION('',(1.,0.,0.));
#17=AXIS2_PLACEMENT_3D('',#14,#15,#16);
#18=BLOCK('BOUNDING BOX OF FINAL PART',#17,175.,113.9,30.);
#19=WORKPIECE('FINISHED PART',#7,0.001,#13,$,#18,());
#20=CARTESIAN_POINT('',(0.,0.,0.));
#21=MILLING_TECHNOLOGY($,.CCP.,$,100.,0.1,$,$,$,$);
#22=CUTTING_COMPONENT(123.,$,987.,#21);
#23=ENDMILL('ENDMILL 40MM',(#22,#22,#22,#22),123.,40.,60.,.RIGHT.,.F.,
4,0.2,0.);
#24=MILLING_MACHINE_FUNCTIONS(.F.,$,.F.,.F.,$,(),.F.,$,$,());
#25=BOTTOM_AND_SIDE_FINISH_MILLING($,$,
'OPERATION FOR FINISH MILLING OF A STEP',10.,#20,#23,#21,#24,4.,$,$,$,
8.,5.,0.,0.);
```

```
▼<Project name="PROJECT" ID="341">
  <Its_id name=""/>
 ▼<Main_workplan name="WORKPLAN" ID="335">
   <Its_id>MAIN WORKPLAN</Its_id>
  ▼<Its_elements name="WORKPLAN" ID="54">
     <Its_id>WORKPLAN FOR FIRST SETUP - STEP</Its_id>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="40">...</Its_elements>
    ▶<Its_setup name="SETUP" ID="53">...</Its_setup>
   </Its_elements>
  ▼<Its_elements name="WORKPLAN" ID="279">
     <Its_id>WORKPLAN FOR SECOND SETUP - SIDE WITH SLOTS</Its_id>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="83">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="109">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="122">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="145">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="154">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="170">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="184">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="188">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="192">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="206">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="211">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="260">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="261">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="262">...</Its_elements>
    ▶<Its_setup name="SETUP" ID="278">...</Its_setup>
   </Its_elements>
  ▼<Its_elements name="WORKPLAN" ID="334">
     <Its_id>WORKPLAN FOR THIRD SETUP - SIDE WITH NO SLOTS</Its_id>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="280">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="304">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="322">...</Its_elements>
    ▶<Its_elements name="MACHINING_WORKINGSTEP" ID="328">...</Its_elements>
    ▶<Its_setup name="SETUP" ID="333">...</Its_setup>
   </Its_elements>
  </Main_workplan>
 ▶<Its_workpieces name="AGGREGATE">...</Its_workpieces>
 ▶<Its_owner name="PERSON_AND_ADDRESS" ID="337">...</Its_owner>
 ▶<Its_release name="DATE_AND_TIME" ID="340">...</Its_release>
  <Its_status/>
</Project>
```

Figure 2: Comparison of Original STEP-NC File and XML Format

3.3 Formation of Knowledge base

Knowledge base for this framework is formed by extracting the feature and operation entity out from the executed machining workingsteps. The feature entity will contain “What” the feature is, i.e. feature geometry information. Operation entity contains information on the type of machining strategy which the CNC machine must use to machine the specified feature. The workingsteps are converted into XML format during execution and uploaded on to the DT.

During the execution of a workingstep, each MTDT parameter value is recorded directly into the SQL server through an adapter software. The STEP-NC feature and operation information extracted from the executed workingstep is correlated with the physical behaviours of the CNC machine within the model defined in the SQL server. Physical behaviours in this case include tool vibration, cutting force, axis velocity, axis acceleration, motor load and tool acoustic emissions.

Each CNC machine will have its own physical characteristics as it will have a different background on what operation it has carried out in the past. Quality of the final machined part will vary across each machine as they will have different physical characteristics such as rigidity, cutting tool condition and material of the machine. These physical characteristics will vary over the lifetime of the machine which will take a significant effect on the final machining quality. These slow varying parameters of the CNC machines cannot be directly modelled into the DT as they are constantly changing over time. Therefore, changes in machine physical properties must be identified from the data reflected on the MTDT by extracting its characteristics. Characteristics of these physical parameters must be correlated to the input STEP-NC data to develop a detailed understanding of the relationship between the feature geometry and physical machine behaviour and machine physical properties.

3.4 Machining Parameter Optimization and Real-Time Monitoring

Once a knowledge base of an appropriate size is established through a number of machining sessions, it can be utilized for both machining process optimization and real-time abnormality detection. The machining parameter optimization algorithm will analyse the new machining workingsteps before the CNC machine executes any motion. This machine parameter optimization algorithm will compare the input feature and operation data with the past machining data stored in the SQL server to derive an optimal machining parameter value. The machining parameter values will be optimized to maximize the final machining feature quality based on the machine’s physical characteristics.

Real-time data from the MTDT will be monitored by the abnormality detection algorithm to detect any unexpected behaviours of the physical machine tool during its operation. This algorithm will utilize the past machining data contained in the SQL server and machine learning algorithm to detect the abnormal behaviour of the machine too during its machining process. Any abnormal behaviours detected by this algorithm is recorded into the SQL server, and an appropriate control signal is sent to the MTDT to minimize the effect. As OPC UA is a bidirectional communication protocol, control commands can be transferred from the DT into the CNC interface to control the physical CNC machine.

4 CASE STUDY

Standard three-axis CNC milling machine can be broken down into four main subsystems which are all controlled under the CNC motion controller to achieve the required machining motion; spindle, linear x-axis, linear y-axis and linear z-axis. The DT of the CNC milling machine is modelled by mapping each of these physical subsystems to an object within the OPC UA server address space. The OPC UA object will be the parental object to a variable object where the live numerical data is stored. Each OPC UA object will represent a subsystem of the CNC machine with variable objects as their children representing its physical and numerical attributes. An OPC UA object will also be made to store the machining data obtained from the STEP-NC file which includes the machining workingsteps and cutting tool information. The input to the MTDT is obtained from two sources: the CNC interface connected to the machine controller and the Data Acquisition (DAQ) card interfacing with the sensors attached to the CNC machine tool.

The structure of the OPC UA information model used in this case study is presented in Figure 3. Each linear axis subsystem has child variable objects to monitor the computed position, offset position, axis velocity, axis acceleration, axis motor current and cutting force.

Accelerometer and current sensors are attached to the tool holder of the CNC milling machine to capture the physical behaviour of the cutting tool along with its motor load during the machining process.

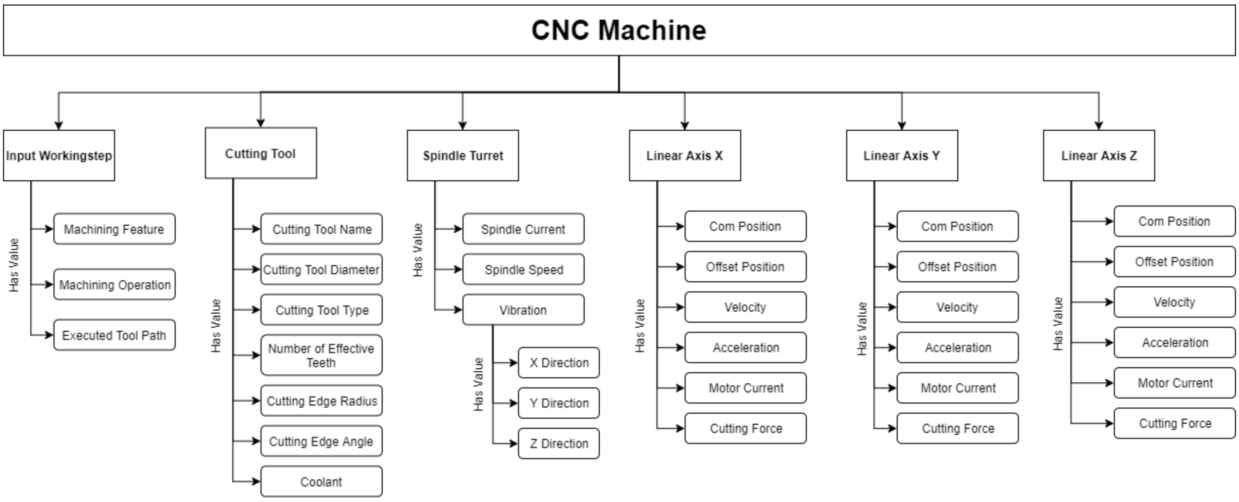

Figure 3: OPC UA Information Model Structure

Figure 4 shows the user interface of the OPC UA client software developed based on the software development kit (SDK) provided from the OPC Foundation which composes of three sections: OPC UA server items, OPC UA node notifications and node value plot. Top right-hand pane displays the address space of the OPC UA server which implements the proposed information model structure. OPC UA node "EMCO Concept 105" takes the place of "CNC Machine" object shown in Figure 3 as this is the model name of the CNC milling machine modelled by this information model. Top left-hand pane displays the OPC UA objects monitored by the client which will be the entire information model. Live values of each monitored object are tracked by the client and recorded to the specified SQL server and visually represented by the plotting window on the bottom pane.

A CNC interface is developed on C# platform to allow STEP-NC machining capabilities on standard CNC milling machines which do not have an open architecture. The developed CNC interface (Figure 5) is capable of visualizing the input STEP-NC data using CADability software package and displaying the data in tree view format on the left-hand pane. This CNC interface acts as an OPC UA client which is responsible for uploading the CNC linear axis position, velocity and acceleration to the MTDT inside the OPC UA server. STEP-NC data is transferred into the OPC UA server by converting it into an XML format. This interface automatically generates the initial toolpath and machining volume calculation when the STEP-NC file is loaded.

The MTDT in the OPC UA server is embedded in an adapter software that logs all the value changes that occur for every variable object into the predefined MS SQL Server database. This predefined MS SQL database has a similar structure to the DT modelled in OPC UA server. Each executed workingstep data along with the machine tool physical data is stored under a single object "MachiningSession" in the database. This single object will correlate every data obtained during the execution of each workingstep. When any data is logged from the MTDT into the SQL server, it will be timestamped by the OPC UA server timer. As each logged data is timestamped, there will be a chronological relationship between each data, allowing understanding of "what" happened at each time.

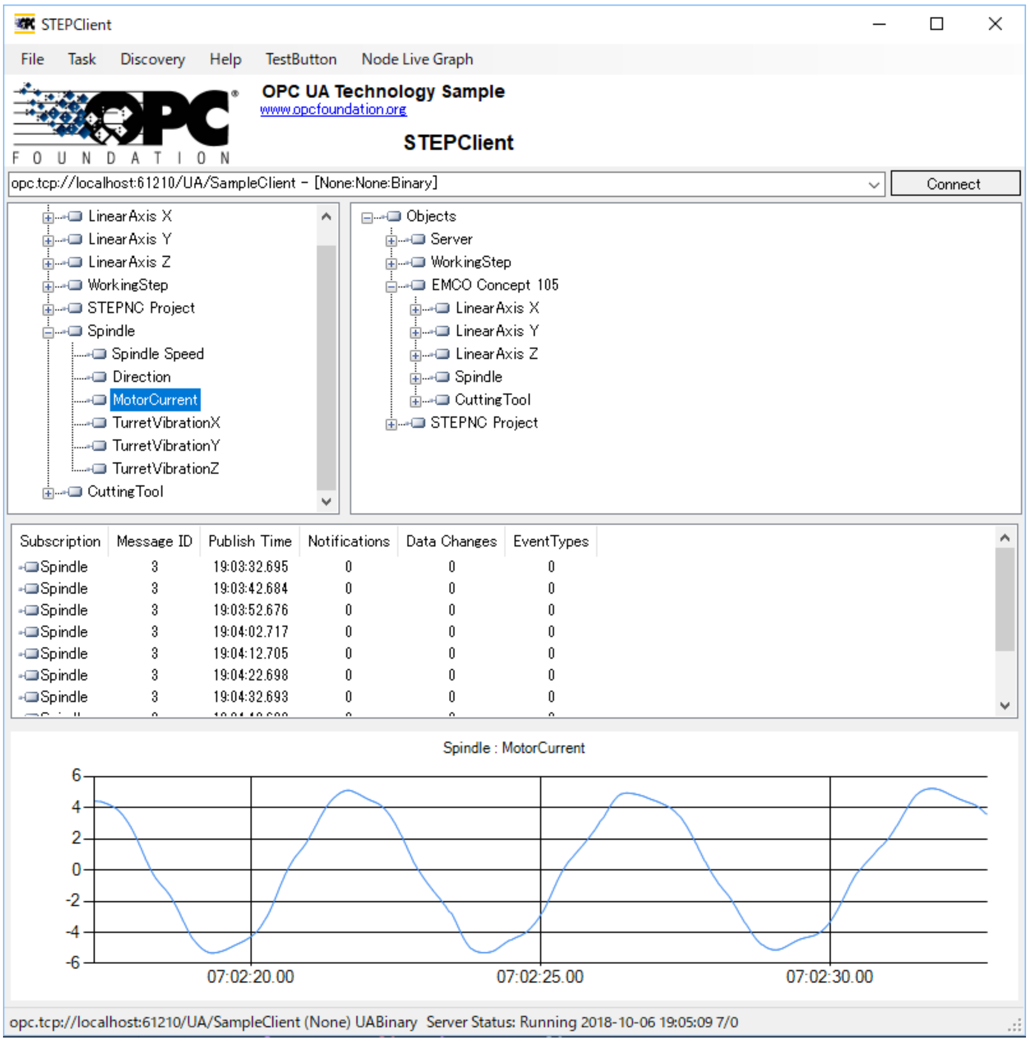

Figure 4: OPC UA Client Software Interface

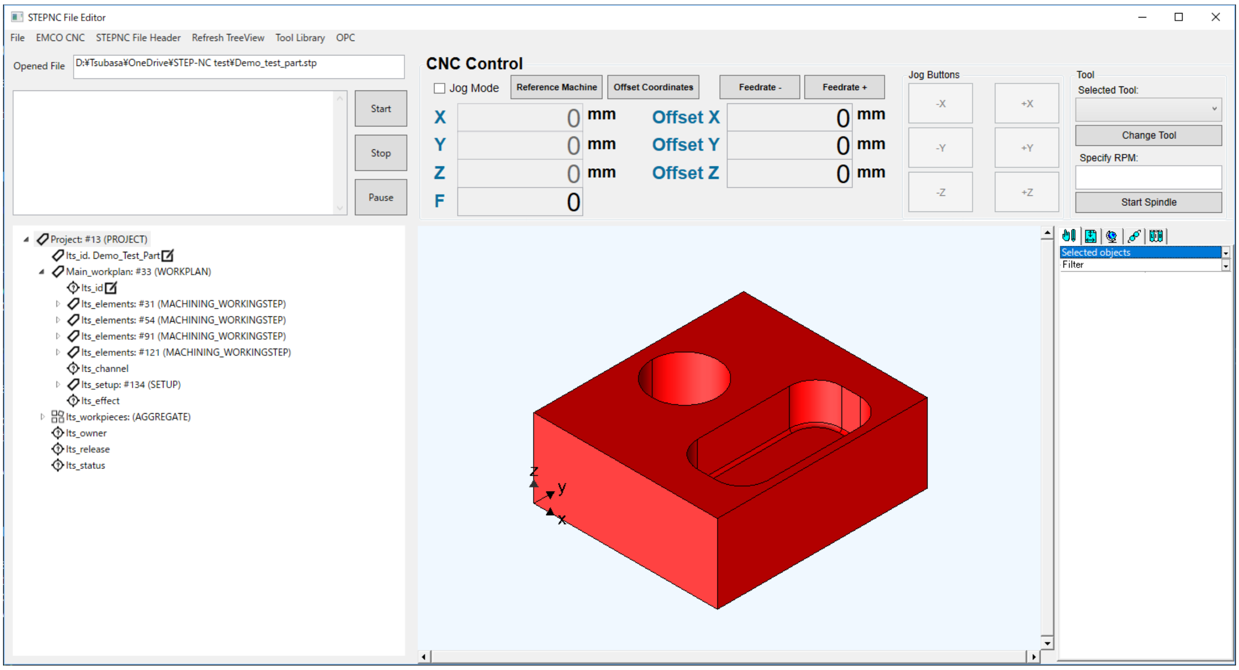

Figure 5: STEP-NC CNC Interface

Additional triaxial accelerometer and current sensors are integrated into the CNC machine tool to capture the physical behaviour of the machine tool during the machining session. Sensor data are collected through National Instrument DAQ card cDAQ9133 containing software which is able to connect to the specified OPC UA server directly. All sensor data captured by the DAQ are uploaded on each appropriate variable node in the OPC UA server. The accelerometer is mounted onto the machine tool turret to capture the vibration occurring on the cutting tool during machining. As the vibration of the cutting tool is measured in three axes: x, y, and z, it is able to capture exactly how the cutting tool is behaving during the machining operations. The current sensor is installed directly on the axis motor driver circuitries to measure the amount of electrical current drawn by the motor during the machining process. Each axis drive motor is connected to a lead screw to precisely control the position, hence by measuring the current drawn by the motor allows to determine the axis drive force.

5 CONCLUSION AND FUTURE WORK

In this paper, a framework for machining parameter optimization with the use of STEP-NC and DT is proposed. This framework demonstrates how STEP-NC machining data can be correlated with real-time physical machine data to establish a knowledge base. The data in the knowledge base are analysed by machine learning algorithms to determine the machine tool specific physical characteristics. Throughout the life of this framework, new machining data will be added to the knowledge base from the MTDT. By constantly analysing new machining data obtained from the MTDT, slow changes of the physical machine characteristics can be detected.

The physical machine characteristics revealed from data analysis enable machine-specific optimization of the input STEP-NC machining data. A machine-specific optimization allows to reduce the variance in machining quality across different machine tools once an appropriate knowledge base is established. The physical machine characteristics also enable detection of abnormal machining behaviour during its operation. As the DT proposed in this framework is formed on OPC UA, a compensation action for the detected abnormality can be executed through the MTDT.

The proposed framework holds a significant amount of flexibility with the incorporation of a machine learning algorithm. For future work, different types of machine learning models will be explored to perform optimization on the feature geometry as well as its machining parameters. The analysis through different machine learning algorithms will help reveal the physical machine characteristics. Therefore, if a sufficient amount of data is stored in the knowledge base, final machine tolerances can be predicted from the input machining data. An effective process planning system can be developed if an accurate prediction can be made from the input STEP-NC file, the workingsteps and workplan orders can be altered for optimal machining time or quality. More sensors will be added in the future to capture the physical behaviour in more detail as there are numerous factors involved to determine the final machining quality of the machined part.

6 REFERENCES

[1] **Oztemel, E., Gursev, S.** 2018. Literature review of Industry 4.0 and related technologies. *Journal of Intelligent Manufacturing*. doi:10.1007/s10845-018-1433-8.

[2] **Grieves, M.** 2014. Digital Twin: Manufacturing Excellence through Virtual Factory Replication. *White paper*.

[3] **Xu, X.** 2017. Machine Tool 4.0 for the new era of manufacturing. *International Jornal of Advanced Manufacturing Technology*. 92(5-8), pp 1893–1900. doi:10.1007/s00170-017-0300-7.

[4] **ISO.** 1982. ISO 6983/1 – Numerical control of machines – Program format and definition of address words – Part 1: Data format for positioning, line and contouring control systems. First edition.

[5] **ISO.** 2007. ISO 10303-238, Industrial Automation Systems and IntegrationProduct Data Representation and Exchange, Part 238: Application Protocol: Application Interpreted Model for Computerized Numerical Controllers.

[6] **Lee, E. A.** 2006. Cyber-physical systems - Are computing foundations adequate?. Position Paper for NSF Workshop on Cyber-Physical Systems: Research Motivation, Techniques and Roadmap, vol. 2, pp 1–9.

[7] **Lee, E. A.** 2008. Cyber physical systems: Design challenges. Proceedings of the 11th IEEE Symposium on Object Oriented Real-Time Distributed Computing (ISORC), Florida, USA, 5-7 May, pp 363–369.

[8] **Liu, C., Jiang, P.** 2016. A Cyber-physical System Architecture in Shop Floor for Intelligent Manufacturing. Procedia CIRP, 56, pp 372–377. doi:10.1016/j.procir.2016.10.059.

[9] **Verl, A., Lechler, A., Schlechtendahl, J.** 2012. Glocalized cyber physical production systems. *Production Engineering*, 6(6), pp 643-649. doi:10.1007/s11740-012-0418-2.

[10] **Wang, L., Törngren, M., Onori, M.** 2015. Current status and advancement of cyber-physical systems in manufacturing. *Journal of Manufacturing Systems*, 37, pp 517–27.

[11] **Dombrowski, U., Wagner, T., Riechel, C.** 2013. Concpt for a Cyber Physical Assembly System. Proceedings of the 2013 IEEE International Symppsium on Assembly and Manufacturing (ISAM), Xi'an, China, July 30 – August 2, pp 293–296. doi:10.1109/ISAM.2013.6643461.

[12] **Lee, J., Bagheri, B.** 2015. Cyber-physical systems in future maintenance. *9th WCEAM Research Paper*, Springer, pp 299–305. doi:10.1007/978-3-319-15536-4.

[13] **Morgan, J., O'Donnell, G.E.** 2015. Cyber physical process monitoring systems. *Journal of Intelligent Manufacturing*, 29(6), pp 1317–1328. doi:10.1007/s10845-015-1180-z.

[14] **Liu, C., Xu, X.** 2017. Cyber-physical Machine Tool - The Era of Machine Tool 4.0. *Procedia CIRP*, 63, pp 70–75. doi:10.1016/j.procir.2017.03.078.

[15] **Liu, C., Vengayil, H., Zhong, R.Y., Xu, X.** 2018. A systematic development method for cyber-physical machine tools. *Journal of Manufacturing Systems*, pp 1–12. doi:10.1016/j.jmsy.2018.02.001.

[16] **ISO**. 2002. ISO 14649-1. Data model for computerized numerical controllers: part 1 overview and fundamental principles. ISO TC 184/SC 1.

[17] **Ridwan, F., Xu, X., Liu, G.** 2012. A framework for machining optimisation based on STEP-NC. Journal of Intelligent Manufacturing, 23 (3), pp 423–441. doi:10.1007/s10845-010-0380-9.

[18] **ISO.** 1994. ISO 10303-11. Industrial automation systems and integration— product data representation and exchange-part 11: Description methods: The EXPRESS language reference manual.

[19] **Zhao, F., Xu, X., Xie, S.** 2008. STEP-NC enabled on-line inspection in support of closed-loop machining. *Robotics and Computer-Integrated Manufacturing*, 24(2), pp 200–216. doi:10.1016/j.rcim.2006.10.004.

[20] **Danjou, C., Le Duigou, J., Eynard, B.** 2015. Closed-loop manufacturing, a STEP-NC process for data feedback: a case study, *Procedia CIRP*, 41, pp 852-857. doi:10.1016/j.procir.2015.12.034.

[21] **Wosnik, M., Kramer, C., Selig, A., Klemm, P.** 2006. Enabling feedback of process data by use of STEP-NC. *International Journal of Computer Integrated Manufacturing*, 19(6), pp 559–69. doi:10.1080/09511920600622080.

[22] **Mahnke, W., Stefan-Helmut, L., Damm, M.** 2009. *OPC Unified Architecture*. Springer Science & Business Media.

[23] **ISO**. 2003. ISO10303-28. Industrial automation systems and integration — Product data representation and exchange — Part 28: Implementation methods: XML representations of EXPRESS schemas and data.