International Journal of Integrated Engineering, Vol. 3 No. 1 (2011) p. 32-37

Employing Actual Shop-floor Status and Machine Tool Kinematic Data Model in Machining Simulation

Aini Zuhra Abdul Kadir[1,2*], **Xun Xu**[1], **Firman Ridwan**[1,3]

[1]Department of Mechanical Engineering, School of Engineering, University of Auckland, New Zealand.
[2]Department of Manufacturing and Industrial Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, Malaysia.
[3]Department of Mechanical Engineering, Andalas University, Indonesia.

Received 24 June 2011; accepted 7 July 2011, available online 21 September 2011

Abstract: In machining simulation, there is always a trade-off between high level of accuracy, and an abstraction of reliance and truthful simulation environment. Most research work has been devoted towards developing precise models and algorithms, yet still lack the capability to portray the true machining environment. This is due to the difficulty in providing a simulation model of data integrity without continually monitoring the shop-floor activities. This factor is compounded by the use of low language data at shop-floor level that hinders the possibility for design data integration. It must be noted that, shop-floor activities are dynamic in nature. Even just prior to machining, machining parameters, cutting tools, workpiece and fixture orientations were adjusted where most of these activities are not being captured and considered in the simulation model. This paper introduces a near-real solution to cater for an ingenuous machining simulation environment. The approach taken is by employing machine tool kinematic data model based on STEP/STEP-NC and actual shop-floor status via MTConnect.

Keywords: Machining simulation, STEP-NC, MTConnect, monitoring, machine tool.

1. Introduction

Over the years, machining simulation has made great strides by allowing manufacturers to emulate, predict, analyze and optimize machining operations. The ability of this technology to imitate real machining condition such as complex interaction of machining parameters, cutting tools, machine tools and control, has made it a powerful tool for decision making that assist managers, engineers and process planners to continuously improve the machining performance. However, in many situations, operators and manufacturing engineers continue to make adjustments and modifications within the shop-floor environment without reference to the simulation model. The reason is mainly due to the ever-changing atmosphere at shop-floor level where most of these activities are not being captured and considered in the simulation model. Small changes in any of the production layout, setup, condition, tools and equipment can result in large changes in the simulation prediction outcome, and even larger changes in the future machining plan. Hence, this incurred unnecessary time added upon machining. More often, the simulation models are developed based on static and idyllic machine condition which does not reflect the definite machine status at shop-floor. Thus, most machining process requires complete re-evaluation of the corresponding simulated output. Although most simulation systems are able to generate NC code (G-code and M code) for machining operations, the codes could not be directly used, due to proprietary machine functions that differ from one machine tool vendor to another.

Ideally, machining simulation must require a series of end-to-end standards that begin from design, transitioning to process planning systems that allows efficient machining to be conducted, and finally, down to actual machining process where any information flow from one end to another must be made possible. However, this is not currently feasible. This is partly due to the lack of a full and comprehensive information in the low level NC code format, that are currently the core representation of most CNC system structure. In addition, simulation models are cut off from real environment. Until now, machine tool monitoring remains a largely unexploited area for connecting real-time shop-floor data into the design environment. Machine monitoring serves as an analysis and diagnostic tool that offers greater visibility into manufacturing processes and help determine ways for improving operation and increasing productivity [1].

Therefore, a good compromise between monitoring low-level environment at shop-floor and high-level design data must be realized. Recently, the emergence of STandard for the Exchange of Product model data (STEP/ISO 10303) [2], STandard for the Exchange of Product model data for Numerical Control (STEP-NC/ISO 14649) [3] as well as MTConnect [4] standards open up new possibilities that will hold complete machining information as well as exchange of data across the design-machining chain [5].

A few simulation studies have been conducted and implemented in utilizing shop-floor data targeted at various types of applications. A virtual machining model for analyzing the sustainability impacts of machining

*Corresponding author: : aabd115@aucklanduni.ac.nz

penerbit.uthm.edu.my/ojs/index.php/ijie

process has been studied recently [6]. Here, real world data such as machine specification data, Life cycle analysis data, cutting speed, feed-rate, energy etc. was collected to determine the environmental impact factor. An extension work was conducted to incorporate LCA parameters into Discrete Event Simulation (DES) that was based on statistical characterization of shop floor process such as cycle time, idle time and failure rates [7-9].

Within STEP-NC domain, machining simulation studies have been expanded but are still bounded towards providing simple simulation analysis such as tool path simulation, NC code generation and feed-speed optimization [10, 11]. This paper presents an investigation into obtaining the actual status at shop-floor level using network protocol (MTConnect) by means of sensors and the integration of the information obtained from high level design data (STEP/STEP/NC). The work reported here is part of the research corresponding to the extraction of network data via MTConnect. Section 2 explains the system implementation utilizing MTConnect for low-level data extraction and STEP/STEP-NC as the data model. Section 3 presents the results and discussions. And finally, the conclusions are drawn in Section 4.

2. System Implementation

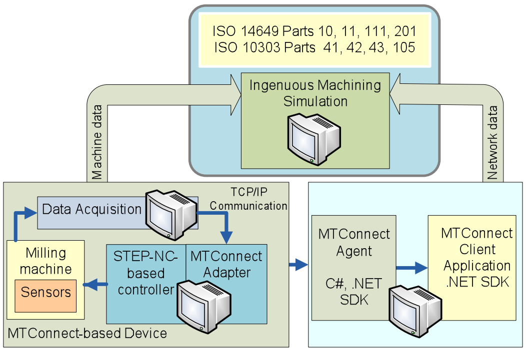


Fig. 1 Ingenuous Machining Simulation via STEP/STEP-NC and MTConnect.

Any machining simulation system model should be easily maintained, shared and adopted to any machining environment without further modifications. The essential architecture of such system is illustrated in Fig. 1. The system composed of:

(i) Low-level data extraction by means of sensors. Under the machining simulation environment, the user will have the option to capture the data either directly from a machine tool or through network protocol (MTConnect). Sensors such as proximity and encoders are utilized to provide real-time data from the machine tool. The data are streamed to assist the machining simulation system with updated information of the machine tool status.

(ii) High-level data structure based on ISO10303/ISO14649 standards. It represents an object-oriented concept that consists of complete information to hold design and machining data. This complete information data model supersedes the limitation of legacy NC-programming approach that only caters description of machining methods instead of allowing more intelligent simulation analysis to be conducted.

2.1 Low-level Data Extraction for Shop-floor Status

In this study, the extraction of information of machine tool status at shop-floor is conducted by utilizing online monitoring system approach called MTConnect. MTConnect is a set of open and royalty-free standards aims to provide interoperability between machine tool controls, devices and software applications by publishing data over networks using the Internet Protocol. By this way, monitored data at shop-floor can be published online and monitored at a remote place. MTConnect has the ability to transfer data such as [4]:

- Static data which include a machine tool identity (i.e. model number, serial number, calibration data, etc.), identity of all independent components of the device (i.e. type of controller, etc.) and device's design characteristics (i.e. axis length, maximum speeds capabilities, device thresholds, etc.).
- Dynamic data captured in real or near-real-time (i.e. current speed, position data, temperature data, program block, etc.) by a device that can be utilized by other devices or applications (e.g. utilized by maintenance diagnostic systems, management production information systems, CAM products, etc.).

The MTConnect physical architecture consists of four items; MTConnect Device, MTConnect Adapter, MTConnect Agent and MTConnect Client application. The Device is composed of components such as STEP-NC based controller [12], sensors and machine tool itself. The Adapter acts as an interface for streaming the data from the data acquisition system and communicates with the Agent. The Agent receives and stores the signals via communication protocol that are accessible through the Web. The Agent will handle all the incoming application requested by the Client. In this study, dynamic data such as position, velocity, and acceleration of X, Y and Z axis as well as spindle speed are captured in order to provide current position or placement of the machine tool elements.

The integration of the captured signals data from machine tool with high-level information such as kinematics representation and tolerance are important in providing precise and accurate simulation models. Therefore, a comprehensive data structure that can provide complete information to support ingenuous machining simulation is needed.

2.2 High-level Data for Machining Simulation

The machining simulation data model are structured to include information such as machining workingsteps, features information, tolerances, machine tool description, kinematics representation and cutting tool description. This high-level information is based on STEP (ISO10303) of Part 41 [13], Part 42 [14], Part 43 [15] and Part 105 [16] as well as STEP-NC (ISO14649) of Part 10 [3], Part 11 [17], Part 111 [18] and Part 201 [19]. These standards only provide a data structure for the needed information. The native or actual data will be stored in a STEP Physical file called Part 21 file [20].

As an example, this study focused on demonstrating a simulation that can portray the true position of the workpiece with respect to other associated elements. To achieve this, the machine tool kinematic is modeled by referring to kinematic structure schema defined under ISO 10303 of Part 105 [16]. This standard specifies an information model for the kinematic aspects that are suitable to represent the kinematics behaviour of a machine tool. For instance, the allied coordinate system of a typical knee-column milling machine with respect to the fixture, workpiece and features placements is illustrated in Fig. 2.

A mechanism specifies the capability of relative motion of links under the constraints imposed by its joints. Generally, two mechanisms are used to represent the coordinate systems of a typical machine tool [21]. The mechanisms go from base to the feature points (workpiece mechanism) and base to the tip of the cutting tool (tool mechanism). The topological aspect of the kinematic representation is specified by kinematic_structure.

Every kinematic_structure is described in terms of its joints and links. Kinematic_joint describes the relationship between two inter-connected and ordered links. The orientation is defined from the first link (through which the joint is entered) to the second link (through which the joint is left). This link is represented as kinematic_link. Kinematic_pair defines kinematic constraints between two adjacent links coinciding at a joint. The types of kinematic constraints include prismatic_pair, revolute_pair, cylindrical_pair, spherical_pair, screw_pair, universal_pair, planar_pair, gear_pair, unconstrained, fully constrained, rack and pinion, point on surface, sliding surface, rolling surface, point on planar curve, sliding curve and rolling curve.

A placement describes the relative position and orientation of a point with respect to another frame. There can be multiple methods to represent positioning of the pair placement. Some of them include rigid homogenous matrix, Axis2_placement_3D, transform and su_parameters. In this study, the Axis2_placement_3D is selected to represent the Cartesian point coordinates for the elements' placement. This entity defines the location and orientation of three mutually perpendicular axes. Its attributes include two directional vectors defined by entity Direction.

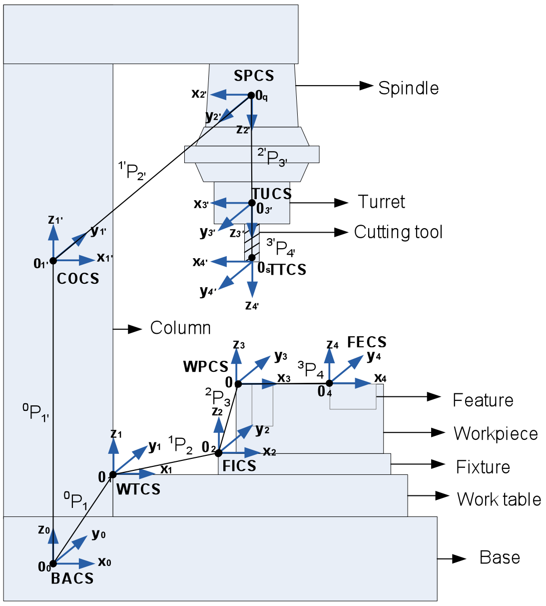


Fig. 2 Kinematic model of a knee-column milling machine.

Two direction vectors (axis and ref_direction) are required to complete the definition of the placement coordinate system. The axis is the placement of Z axis direction and the ref_direction (RefDirection) is an approximation to the placement of X axis direction [14]. Therefore, a kinematic chain can be generated with relative to the specified placement of a former coordinate system.

From Fig. 2, the two mechanisms used in representing the workpiece and tool mechanisms can be observed. The workpiece mechanism includes the joint for base, work table, fixture, workpiece and feature with coordinate system annotated as BACS, WTCS, FICS, WPCS, and FECS, respectively. While the tool mechanism includes the base, column, spindle, turret and cutting tool tip with coordinate system annotated as BACS, COCS, SPCS, TUCS, and TTCS, respectively.

The transformation of the coordinated system from CS_i to CS_k can also be modeled using Homogeneous Transformation Matrix (HTM) P denoted by ${}^k\mathbf{P}_i$ [22]. Mathematically, the linear transformation can be represented by Eq. 1:

$$ {}^k P_i = \begin{bmatrix} & 3x3 & & \delta x \\ & \text{rotational} & & \delta y \\ & \text{matrix} & & \delta z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

where $\delta x, \delta y, \delta z$ are the components of the translation vector in X, Y, and Z directions. While, the rotation transformation can be formulated as follows:

$$\mathbf{R_x} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x & 0 \\ 0 & \sin\theta_x & \cos\theta_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$\mathbf{R_y} = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$\mathbf{R_z} = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 & 0 \\ \sin\theta_z & \cos\theta_z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where R_x is the rotation of the coordinate system around the X axis, R_y is the rotation of the coordinate system around the Y axis, R_z is the rotation of the coordinate system around the Z axis, and $\theta_{x,}\theta_{y,}\theta_z$ represents the rotation angle around the respective axes. Thus, the transformation of workpiece mechanism can also be modeled through the HTM equation resulting in,

$$\mathbf{{}^0P_4 = {}^0P_1\, {}^1P_2\, {}^2P_3\, {}^3P_4} \quad (5)$$

Where,

$$\mathbf{{}^0P_1} = \begin{bmatrix} 1 & 0 & 0 & x_1 \\ 0 & 1 & 0 & y_1 \\ 0 & 0 & 1 & z_1 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{{}^1P_2} = \begin{bmatrix} 1 & 0 & 0 & x_2 \\ 0 & 1 & 0 & y_2 \\ 0 & 0 & 1 & z_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{{}^2P_3} = \begin{bmatrix} 1 & 0 & 0 & x_3 \\ 0 & 1 & 0 & y_3 \\ 0 & 0 & 1 & z_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \text{and}$$

$$\mathbf{{}^3P_4} = \begin{bmatrix} 1 & 0 & 0 & x_4 \\ 0 & 1 & 0 & y_4 \\ 0 & 0 & 1 & z_4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Similarly, the transformation of tool mechanism is also achieved through the HTM equation resulting in,

$$\mathbf{{}^0P_{4'} = {}^0P_{1'}\, {}^{1'}P_{2'}\, R_x\, {}^{2'}P_{3'}\, {}^{3'}P_{4'}} \quad (6)$$

Where,

$$\mathbf{{}^0P_{1'}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z_{1'} \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{{}^{1'}P_{2'}} = \begin{bmatrix} 1 & 0 & 0 & x_{2'} \\ 0 & \cos\theta_{2'} & -\sin\theta_{2'} & y_{2'} \\ 0 & \sin\theta_{2'} & \cos\theta_{2'} & z_{2'} \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{{}^{2'}P_{3'}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z_{3'} \\ 0 & 0 & 0 & 1 \end{bmatrix}, \text{and } \mathbf{{}^{3'}P_{4'}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z_{4'} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The summary of associated coordinates and its transformation is tabulated in Table 1.

Table 1 Kinematics notation of workpiece and tool mechanisms.

Mechanism	Coordinate System	Kinematic_link	Cartesian Point		Angle , Өn	HTM
			First link	Second link		
Tool	TUCS - TTCS	Turret - Tool tip	$z_{3'}$	$z_{4'}$	-	$^{3'}P_{4'}$
	SPCS - TUCS	Spindle - Turret	$z_{2'}$	$z_{3'}$	-	$^{2'}P_{3'}$
	COCS - SPCS	Column - Spindle	$x_{1'}y_{1'}z_{1'}$	$x_{2'}y_{2'}z_{2'}$	$\Theta_{2'}$	$^{1'}P_{2'}$ & R_x
	BACS - COCS	Base - Column	z_0	$z1'$	-	$^0P_{1'}$
Workpiece	BACS -	Base - Work Table	$x_0y_0z_0$	$x_1y_1z_1$	-	$^0P_1$
	WTCS - FICS	Work Table - Fixture	$x_1y_1z_1$	$x_2y_2z_2$	-	$^1P_2$
	FICS - WPCS	Fixture - Workpiece	$x_2y_2z_2$	$x_3y_3z_3$	-	$^2P_3$
	WPCS - FECS	Workpiece - Feature	$x_3y_3z_3$	$x_4y_4z_4$	-	$^3P_4$
	FECS	Feature Placement	$x_4y_4z_4$	-	-	-

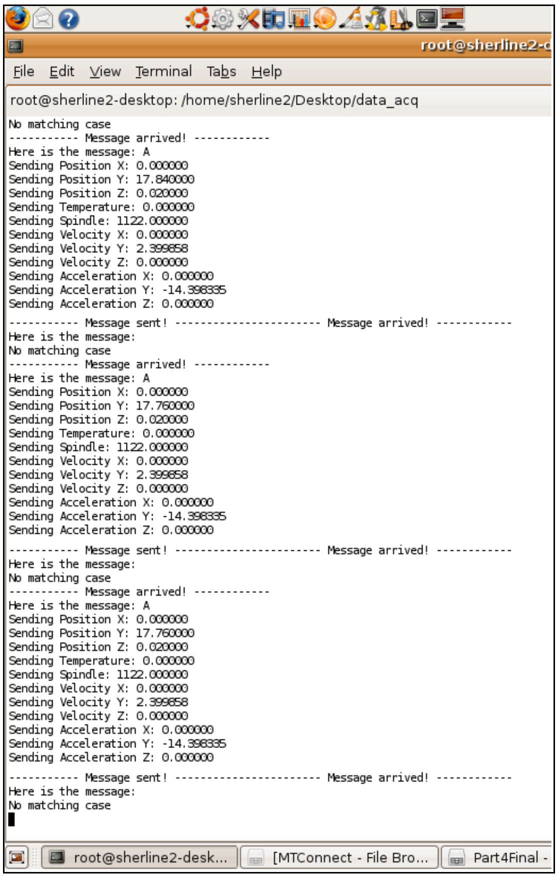
Information from the STEP-NC data structure can be utilized in representing the kinematic chain of these mechanisms. For example, the feature placement under the FECS specified by an entity called Two5D_manufacturing_feature. The entity is used to determine the placement of a specific feature. This placement is relative to WPCS which is defined by the Setup entity [3]. The position and orientation of the FICS can be defined using Setup attribute called its origin. WTCS is represented with relative to FICS. The position of FICS and other machine tool elements (BACS, COCS, SPCS, TUCS, and TTCS) can then be defined using the physical dimension and angles from each of these elements.

Within STEP/STEP-NC, the relationship of how homogeneous transformation matrix is used was established through the connection via the Entity Axis_2D_placement_3D where the coordinates and angles are represented using the entity Direction and RefDirection respectively. Through these entities, the positions of any related elements captured by the sensors can be used to update the Part 21 file in adapting the simulation environment to a true placement of the elements based on actual machine situation.

3. Results and Discussion

At shop-floor, the data are continuously recorded and sent to assist the machining simulation with updated information of shop-floor situation. Fig. 3 provides the snapshot of the data streamed via MTConnect. From the figure, the X, Y, and Z positions are utilized by the simulation model in order to define the exact location of the position of the worktable.

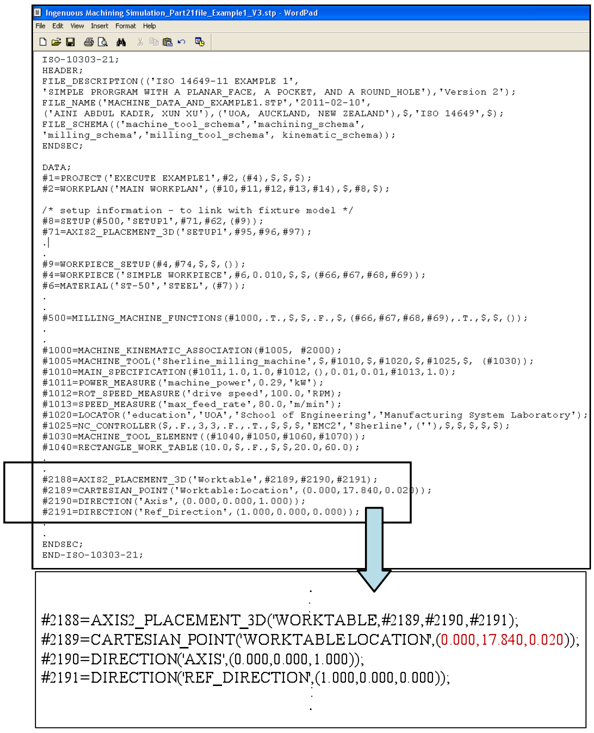
From this value, the coordinates of workpiece can be determined using the WPCS and FECS transformation. Fig. 4 shows an example of Part 21 file. The highlighted values (0.00, 17.84 and 0.02) in the enlarged Part 21 file as shown at the bottom of the figure is referred from the actual value obtained from MTConnect. Thus, these values will then represent the exact location of the worktable positions.



```
root@sherline2-desktop: /home/sherline2/Desktop/data_acq
No matching case
----------- Message arrived! -----------
Here is the message: A
Sending Position X: 0.000000
Sending Position Y: 17.840000
Sending Position Z: 0.020000
Sending Temperature: 0.000000
Sending Spindle: 1122.000000
Sending Velocity X: 0.000000
Sending Velocity Y: 2.399858
Sending Velocity Z: 0.000000
Sending Acceleration X: 0.000000
Sending Acceleration Y: -14.398335
Sending Acceleration Z: 0.000000

----------- Message sent! ---------------------- Message arrived! -----------
Here is the message:
No matching case
----------- Message arrived! -----------
Here is the message: A
Sending Position X: 0.000000
Sending Position Y: 17.760000
Sending Position Z: 0.020000
Sending Temperature: 0.000000
Sending Spindle: 1122.000000
Sending Velocity X: 0.000000
Sending Velocity Y: 2.399858
Sending Velocity Z: 0.000000
Sending Acceleration X: 0.000000
Sending Acceleration Y: -14.398335
Sending Acceleration Z: 0.000000

----------- Message sent! ---------------------- Message arrived! -----------
Here is the message:
No matching case
----------- Message arrived! -----------
Here is the message: A
Sending Position X: 0.000000
Sending Position Y: 17.760000
Sending Position Z: 0.020000
Sending Temperature: 0.000000
Sending Spindle: 1122.000000
Sending Velocity X: 0.000000
Sending Velocity Y: 2.399858
Sending Velocity Z: 0.000000
Sending Acceleration X: 0.000000
Sending Acceleration Y: -14.398335
Sending Acceleration Z: 0.000000

----------- Message sent! ---------------------- Message arrived! -----------
Here is the message:
No matching case
█
```

Fig. 3 Snapshot of the output data obtained via MTConnect.

When the MTConnect is activated from the simulation model, it will give the user an option in capturing this real-time data in order to perform simulation based on the actual machine situation. The velocity and acceleration values are derived from the feed-rate of worktable movement. In this way, these data becomes valuable in determining the exact location of the worktable for more advance analysis.



```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('ISO 14649-11 EXAMPLE 1',
'SIMPLE PRORGRAM WITH A PLANAR_FACE, A POCKET, AND A ROUND_HOLE'),'Version 2');
FILE_NAME('MACHINE_DATA_AND_EXAMPLE1.STP','2011-02-10',
('AINI ABDUL KADIR, XUN XU'),('UOA, AUCKLAND, NEW ZEALAND'),$,'ISO 14649',$);
FILE_SCHEMA(('machine_tool_schema','machining_schema',
'milling_schema','milling_tool_schema', kinematic_schema));
ENDSEC;

DATA;
#1=PROJECT('EXECUTE EXAMPLE1',#2,(#4),$,$,$);
#2=WORKPLAN('MAIN WORKPLAN',(#10,#11,#12,#13,#14),$,#8,$);

/* setup information - to link with fixture model */
#8=SETUP(#500,'SETUP1',#71,#62,(#9));
#71=AXIS2_PLACEMENT_3D('SETUP1',#95,#96,#97);
.
.
#9=WORKPIECE_SETUP(#4,#74,$,$,());
#4=WORKPIECE('SIMPLE WORKPIECE',#6,0.010,$,$,(#66,#67,#68,#69));
#6=MATERIAL('ST-50','STEEL',(#7));
.
.
#500=MILLING_MACHINE_FUNCTIONS(#1000,.T.,$,$,.F.,$,(#66,#67,#68,#69),.T.,$,$,());
.
.
#1000=MACHINE_KINEMATIC_ASSOCIATION(#1005, #2000);
#1005=MACHINE_TOOL('Sherline_milling_machine',$,#1010,$,#1020,$,#1025,$, (#1030));
#1010=MAIN_SPECIFICATION(#1011,1.0,1.0,#1012,(),0.01,0.01,#1013,1.0);
#1011=POWER_MEASURE('machine_power',0.29,'kW');
#1012=ROT_SPEED_MEASURE('drive speed',100.0,'RPM);
#1013=SPEED_MEASURE('max_feed_rate',80.0,'m/min');
#1020=LOCATOR('education','UOA','School of Engineering','Manufacturing System Laboratory');
#1025=NC_CONTROLLER($,.F.,3,3,.F.,.T.,$,$,$,'EMC2','Sherline',(''),$,$,$,$,$);
#1030=MACHINE_TOOL_ELEMENT((#1040,#1050,#1060,#1070));
#1040=RECTANGLE_WORK_TABLE(10.0,$,.F.,$,$,20.0,60.0);
.
.
#2188=AXIS2_PLACEMENT_3D('Worktable',#2189,#2190,#2191);
#2189=CARTESIAN_POINT('Worktable:Location',(0.000,17.840,0.020));
#2190=DIRECTION('Axis',(0.000,0.000,1.000));
#2191=DIRECTION('Ref_Direction',(1.000,0.000,0.000));
.
.
ENDSEC;
END-ISO-10303-21;
```

```
.
.
.
#2188=AXIS2_PLACEMENT_3D('WORKTABLE,#2189,#2190,#2191);
#2189=CARTESIAN_POINT('WORKTABLE:LOCATION',(0.000,17.840,0.020));
#2190=DIRECTION('AXIS',(0.000,0.000,1.000));
#2191=DIRECTION('REF_DIRECTION',(1.000,0.000,0.000));
.
.
```

Fig. 4 Example of Part 21 file.

4. Conclusions

Tremendous progress has been made in developing machining simulation models, whilst two major issues still remain; most of the contemporary simulation systems (i) utilized algorithms that are application specific and lacks a comprehensive data model to integrate shop-floor for providing true status of machine tool condition, and (ii) unable to easily adapt to a new application environments and readily be applied to various machine tool applications. This paper provides an insight vision towards achieving ingenuous machining simulation environment by employing machine tool kinematic data model and actual shop-floor status. The results showed that by utilizing STEP/STEP-NC and MTConnect standards, more advanced simulation analysis can be conducted where valuable information at shop-floor can be captured and utilized. Thus, the imitation of machine tool activities can be retained within one simulation platform.

Acknowledgements

The authors would like to acknowledge the Ministry of Higher Education, Malaysia and Universiti Teknologi Malaysia for the funding and scholarship in support of the research work.

References

[1] Michaloski, J., Lee, B., Proctor, F., Venkatesh, S., and S, L., (August 30 - September 2, 2009), Quantifying the performance of MT-Connect in a distributed manufacturing environment in

Proceedings of the 2009 DETC 2009 ASME International Design Engineering Technical Conferences. San Diego, California, USA.

[2] ISO 10303: Part 1, (1994), Industrial automation systems and integration -- Product data representation and exchange -- Part 1: Overview and fundamental principles.

[3] ISO 14649: Part 10, (2003), Industrial automation systems and integration physical device control-data model for computerized numerical controllers -- Part 10: General process data.

[4] MTConnect Standard, (2009), Part 1 - Overview and protocol, Version 1.01, MTConnect Institute.

[5] Vijayaraghavan, A. and Dornfeld, D., (2010), Automated energy monitoring of machine tools, CIRP Annals - Manufacturing Technology, 59(1): p. 21-24.

[6] Shao, G., Kibira, D., and Lyons, K., (August 15-18,2010), A Virtual Machining Model for Sustainability Analysis. in Proceedings of ASME 2010 International Design Engineering Technical Conference & Computers and Information in Engineering Conference. Montreal, Quebec, Canada.

[7] Michaloski, J., Raverdy, B., Lee, B.E., Proctor, F., Venkatesh, S., Bengtsson, N., and Skoogh, A., (November 12-18, 2010), Push–Button Discrete Event Simulation For Analysis Of Factory Floor Operations. in Proceedings of the ASME 2010 International Mechanical Engineering Congress & Exposition. Vancouver, British Columbia, Canada.

[8] Bengtsson, N., Michaloski, J., Proctor, F., Shao, G., and Venkatesh, S., (October 12-15, 2010), Towards data-driven sustainable machining - Combining MTConnect production data and discrete event simulation. in Proceedings of ASME 2010 International Manufacturing Science and Engineering Conference. Erie, Pennsylvania, USA.

[9] Skoogh, A., Michaloski, J., and Bengtsson, N., (2010), Towards continuously updated simulation models : Combining automated raw data collection and automated data processing in Proceedings of the 2010 Winter Simulation Conference.

[10] Chen, X., Zhang, C., Wang, Q., and Liu, R., (2010), Study on the Simulation System based on STEP-NC, Advanced Materials Research, Transition of Technical Publications,, 129-131: p. 748-752.

[11] Zhu, X., Wang, Y., and Fu, H., (2006), A 3-D simulation system for milling machining based on STEP-NC. Dalian, China: Institute of Electrical and Electronics Engineers Inc.

[12] Ridwan, F., Xu, X., and Liu, G., (2010), A framework for machining optimisation based on STEP-NC, Journal of Intelligent Manufacturing, in press: p. 1-19.

[13] ISO 10303: Part 41, (2000), Industrial automation systems and integration -- Product data representation and exchange -- Part 41: Integrated generic resource: Fundamentals of product description and support.

[14] ISO 10303: Part 42, (1994), Industrial automation systems and integration -- Product data representation and exchange -- Part 42: Integrated generic resources: Geometric and topological representation.

[15] ISO 10303: Part 43, (2000), Industrial automation systems and integration -- Product data representation and exchange -- Part 43: Integrated generic resource: Representation structures.

[16] ISO 10303: Part 105, (1996), STEP Product Data Representation and Exchange: Part 105, Integrated application resource: Kinematics.

[17] ISO 14649: Part 11, (2003), International Organization for Standardization, Data model for Computerized Numerical Controllers -- Part 11: Process data for milling.

[18] ISO 14649: Part 111, (2000), International Organization for Standardization, Data model for Computerized Numerical Controllers -- Part 111: Tools for milling.

[19] ISO 14649: Part 201, (April 2011), Automation systems and integration, Physical device control, Data model for Computerized Numerical Controllers -- Part 201: Machine tool data for Cutting process.

[20] ISO 10303: Part 21, "Industrial automation systems and integration-product data representation and exchange -- Part 21: Implementation methods: Clear text encoding of the exchange structure," ed, 1994.

[21] Matsuda, T., Tanaka, F., Onosato, M., and Date, H., (2008), Development of a Digital Machining Information Model to Support a Real-Virtual Machining System, Journal of Advanced Mechanical Design, Systems, and Manufacturing, 2 (4): p. 597-608

[22] Paul, R.P., (1981), Robot manipulators: mathematics, programming and control, MIT Press, Cambridge, MA.