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A study on the construction of digital twin and disturbance estimation model for parallel link mechanism robot

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Abstract

In recent years, digital twin systems have been attracting attention in the industrial fields where including field machine tools are used, because they enable the prediction of machine tool failure locations and the simulation of machining and operation, leading to improved productivity and reduced costs. In this study, we construct a digital twin of a robotic machine tool with a parallel mechanism that has multiple links. The parallel mechanism robot (XMINI) is expected to be applied to machining operations because it has higher rigidity and output than an industrial robot arm, and has a wider work area and lighter weight than a conventional machine tool. However, there is no guide surface to physically guarantee linearity in parallel mechanisms, unlike conventional machine tools that consist of linear and rotary axes, and errors in all joints are concentrated at the machining point, which causes a problem in accuracy.

This study aims to improve the accuracy by incorporating the disturbance estimation model developed using the kinematic model devised in the previous study into a digital twin to achieve real-time control. Here we report the improvement of the external force estimation method using the sequential kinematics model proposed in the previous study and the results of comparison and verification between the results estimated based on the model and the actual measured values.

Keywords: Digital twin systems, Parallel link mechanism, Disturbance observer, Jacobian matrix

1. Introduction

The parallel mechanism robot (XMINI) is expected to be applied to machining work, because it has higher rigidity and output than an industrial serial robot arm, and has a wider work area and lighter weight than conventional machine tools. However, unlike conventional machine tools, which consist of linear and rotary axes, parallel mechanisms have no guide surfaces to physically guarantee linearity, and errors in all joints are concentrated at the tool point, causing accuracy problems. We believe that XMINI's machining accuracy can be improved by creating a disturbance estimation model using the Jacobi matrix and controlling the machine in real-time by compensating for cutting resistance. A digital twin system was constructed to acquire torque, current, and position used to estimate the disturbance.

Here we report on the construction of a digital twin, a disturbance estimation method, especially for cutting resistance, and the results of comparing and verifying the results estimated based on the model with the actual measured values.

2. Target kinematics machine tool

2.1.Parallel link mechanism robot

The machine tool used in this study is XMINI by EXECHON Co. Figure 1 shows the structure of XMINI. This machine tool is a 5-axis machine tool that combines a 3-DOF parallel mechanism consisting of three extending and retracting axes (1st-3rd axis) and 2-DOF serial mechanisms consisting of two rotating axes (A and C axis). Figure 2 shows the kinematics configuration of XMINI, Table 1 describes each parameter, and Table 2 shows the performance of XMINI.

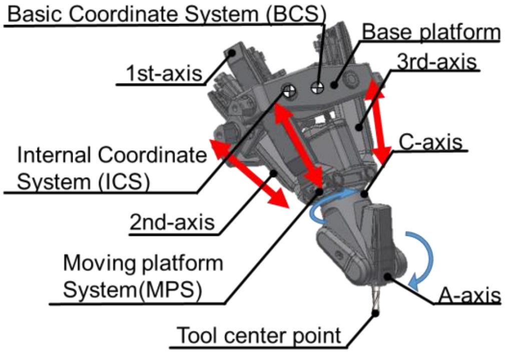

Figure 1 Structure of XMINI

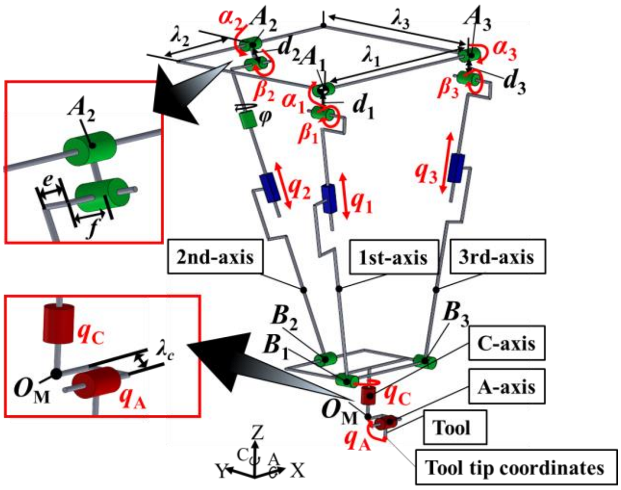

Figure 2 Kinematic configuration of XMINI

Table 1 Geometric parameter

O_{ICS}	Origin of internal coordinate system (A_1)
O_{M}	Origin of moving platform coordinate system
A_i	Point of intersection of base platform and the each axis
B_i	Point of intersection of Moving platform and each axis
q_i	Length of the perpendicular between A_i and B_i
q_{C}	Angle of the C rotary axis
q_{A}	Angle of the A rotary axis
α_i β_i	Angle of the outer, inner universal joint at the base platform
γ_i	Angle of the elbow joint at the moving platform
λ_i	Distance between O and A_2, A_3 along the X, Y direction
λ_{c}	distance between O_{M} and A axis
d_i	Distance between both rotaries of a universal joint
e,f	Possible offsets perpendicular to 2-axis at the base point A_2
φ	Angle between 2-axis about its longitudinal direction

Table 2 Specifications of XMINI

Item		Value	Unit
Axis max speed	1st-axis	60	m/min
	2rd-axis	60	m/min
	3nd-axis	60	m/min
	C-axis	37	min^{-1}
	A-axis	37	min^{-1}
Axis Stroke	1st-axis	300	min^{-1}
	2rd-axis	300	mm
	3nd-axis	300	mm
Axis Rotary	C-axis	±180	degree
	A-axis	-4/+115	degree
Positioning precision		±10	µm
Module weight		250	kg
Repeatability		<5	µm
Spindle	Max speed	20000	min^{-1}
	Diameter	$\varphi 114\ h6$	mm
Motor of each axis	SIEMENS 1T7034-5SK71-1BH1		
Cutting agent	Air		

2.2. System configuration

Figure 3 shows the system configuration. The controller of XMINI is a SIEMENS 840Dsl, the OPCUA is a Takebishi DeviceXPlorer, and the 3D simulation software is Cenit FASTSUITE Edition 2. Data was acquired from the controller via OPCUA, and the model on the 3D simulation software was synchronized with the actual machine based on the acquired data to provide a digital twin system. The acquired data is used to estimate the external force, and the controller is commanded to change the feed rate to maintain a constant cutting resistance. Data is acquired every 60 milliseconds in this system.

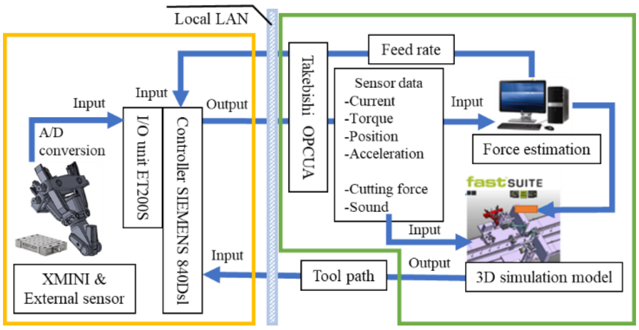

Figure 3 System configuration

3. External force estimation

3.1. Method of external force estimation(Type 1)

Non-linear input-output relationships of robot mechanisms such as parallel link mechanisms can be linearized by focusing on piecewise motions of the mechanism using the Jacobi matrix1). The Jacobi matrix is calculated using the forward kinematics model of XMINI presented in the previous study. The tooltip coordinate S obtained by forward kinematics are shown in Equation (1)2). The tool center point coordinate S as a function of the input Q is expressed in Equation (2). By differentiating Equation (2), the Jacobi matrix can be obtained (Equation (3)).

$$S = R(\theta_0)R(\alpha_1)D_1R(\beta_1)Q_1R(\gamma_1)O_M \\ R(\theta_{CYZ})R(\theta_{CXZ})R(q_c)L_cR(q_A)T \tag{1}$$

$$S = f(Q) \tag{2}$$

$$\Delta S = J\Delta Q \tag{3}$$

Using the Jacobi matrix, the relationship between torque and external force F on the tool tip can be expressed by Equation (4).1)

$$\tau = J^T F \tag{4}$$

Therefore, by deriving the inverse of the transpose matrix J^T of the Jacobi matrix, it is possible to calculate the external force acting on the tooltip using the torque. However, since the Jacobi matrix used in this study is a 3 × 5 matrix, there is no inverse matrix. Thus, the pseudo-inverse matrix defined by Equation (5) is used.

$$X^+ = (X^T X)^{-1} X^T \tag{5}$$

The external force F acting on the tooltip is calculated by Equation (6). $(J^T)^+$ denotes the pseudo-inverse matrix of J^T

$$F = (J^T)^+ T \tag{6}$$

Table 3 shows the definition of each parameters used in the equations.

Table 3 Parameter difinitions

S	Tool center point coordinate
$R(\theta_0)$	Angle of Base platform
$R(\alpha_1)$	Angle of the outer universal joint at the base platform first axis
D_1	Distance between both rotaries of a universal joint of first axis
$R(\beta_1)$	Angle of the inner universal joint at the base platform of first axis
Q_2	Stroke of first axis
O_{M}	Moving platform direction vector and position vector
$R(\theta_{\mathrm{CXZ}})$	Orientation of axis 4 with respect to MPS(Fig.1)
$R(\theta_{\mathrm{CYZ}})$	
$R(q_c)$	C axis rotation matrix
L_c	Distance between C axis and A axis
$R(q_A)$	A axis rotation matrix
T	Tool orientation vector
J	Jacobian matrix
Q	Input value to drive shaft

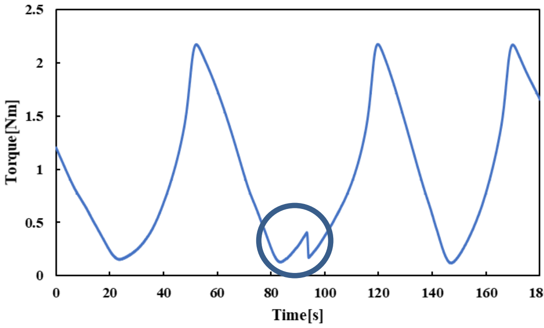

Figure 4 2nd-axis torque

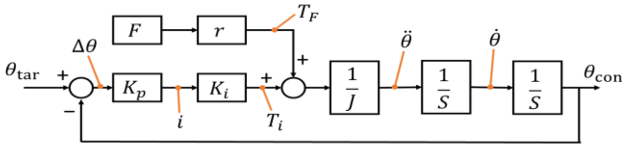

Figure 5 Block diagram of the system configuration for each axis motor

3.2. Improvement of the external force estimation method (Type 2)

Previous studies have reported that the external force estimation method described in the previous section could estimate the timing of load application while it is difficult to estimate the external force. One possible reason we found for this is the influence of the torque fluctuation that is always occurring. We think this torque fluctuation is caused by the control system which tries to maintain the position of the mechanism lowered by gravity. Figure 4 shows the fluctuation of the 2nd-axis torque and the change in torque due to 10 N external force. The circled area shows the change in torque due to load. This figure shows that the fluctuation of the torque always generated has an amplitude of about 2 Nm, and the change in torque due to external force is as small as 0.3 Nm. Therefore, it is necessary to extract only the change in torque due to external force for more accurate external force estimation.

Figure 5 illustrates a simplified block diagram of the system configuration for each axis motor of XMINI. The current *i* is obtained by applying the gain K_p to the difference $\Delta\vartheta$ between the control value θ_{con} and the target value θ_{tar}, and the torque T_i is obtained by applying the torque constant K_i to the current *i*. The total torque *T* is the sum of the torque T_i obtained from the current value, and the external torque T_F generated by the external force *F* and the arm length *r*. Thus, the disturbance torque can be obtained by subtracting the torque $T_i$obtained from the current value from the total torque *T* (Equation (7))

$$T_F = T - K_i \times i \tag{7}$$

The servo motors used in XMINI are SIEMENS SIMATIC S-1FT7 with a torque constant of 0.89 [Nm/A].

3.3. Evaluation of the improved external force estimation method

Evaluation of the improved external force estimation method is conducted. Figure 6 shows the experimental situation and Table 4 shows the specification of digital force gauge used for measuring. The evaluation method is to apply a force to the spindle in the X(+) direction using a digital force gauge as shown in Figure 6. At the same time, data on the applied force and the position, torque, and current of each drive shaft are acquired. The measured force result and the results of estimated force calculated by type 1 and type 2 external force estimation methods are evaluated.

Figure 7 shows the force applied to the spindle. The force was applied in two steps of 20N and 50N from no load applied, and then returned to the no-load. The magnitude of the applied load was set assuming finish machining.

Figures 8, 9, and 10 show the estimated force in the X, Y, and Z directions using type 1, and Figures 11, 12, and 13 show the estimated forces in the X, Y, and Z directions using type 2. Comparing the results from improved estimation method and the original, the trendency of the graph in the X direction is similar, but in type 2, the load is calculated in the Y and Z directions where no load is applied, while in type 1, the load is constant without significant movement. From these results, it can be said that the improved external force estimation method is able to extract only the components that change due to external forces. However, while the maximum load applied was 50 N, it was 300N using type 1 and 2N using type 2, both of which were significantly different from the measured values.

Possible causes are that the Jacobi matrix used does not include the geometrical error of mechanical elements, and that the torque applied to each driven joint is ignored. XMINI has three linear axes and two rotary axes with motors, as well as ten free-rotating driven joints that are dependent on motorized motion. The torque applied to these 10 driven joints cannot be measured by the current system and is ignored when estimating external forces.

To acquire the torque of the driven joints, new sensors are required, and the input elements of the Jacobi matrix increase when mechanism errors and the torque of the driven joints are taken into account. The Jacobi matrix is constantly being updated as the machine's posture changes, because the posture at that moment must be calculated. Also, each increase in the input elements causes an increase in the partial derivatives, which increases the computational complexity.Since we plan to incorporate the system into a digital twin for real-time use in the future, it is not practical to increase the number of input elements because the computational complexity cannot be increased any further.

Currently, the trend in changes of the external force estimation result itself generally agrees with the graph of the given load, and we believe that the accuracy of the external force estimation result can be improved by calibration using the cutting resistance that can be calculated from the spindle torque. Because the composite force obtained from the external force estimation model and the cutting resistance calculated from the spindle torque should match, we believe that the accuracy of the external force estimation results can be improved without a large increase in the amount of calculation by calibrating the results using the composite force.

Figure 6 Measuring method

Table 4 Specification of Digital force gauge

Model	ZTS-50N
Accuracy	±0.2%F.S. ±digit
Measurement unit	N
Display update	16Hz
Sampling speed	Maximum 2000Hz
Usage environment	Temperature 0-40℃ Humidity 20-80%RH
Body wight	About 490g

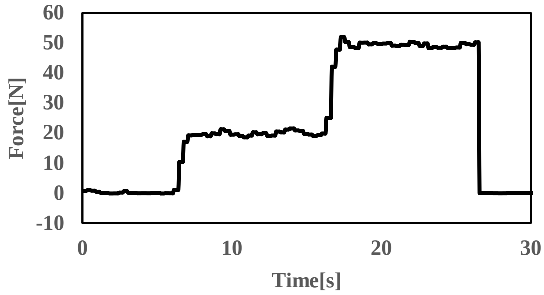

Figure 7 Measurement result of force in X direction

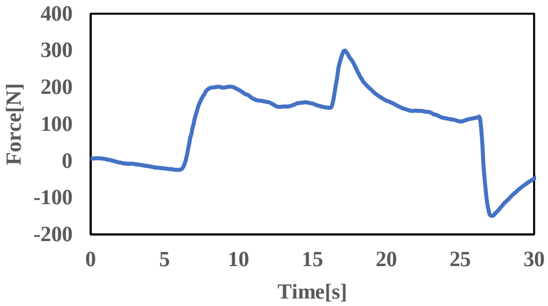

Figure 8 Force estimate result from type1 in X direction

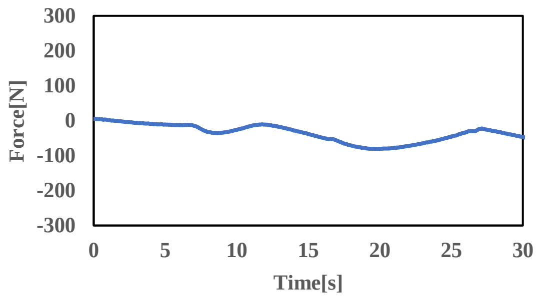

Figure 9 Force estimate result from type1 in Y direction

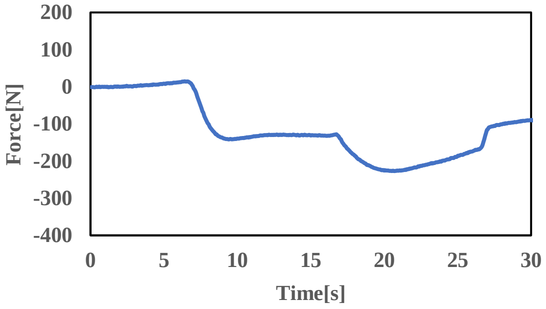

Figure 10 Force estimate result from type1 in Z direction

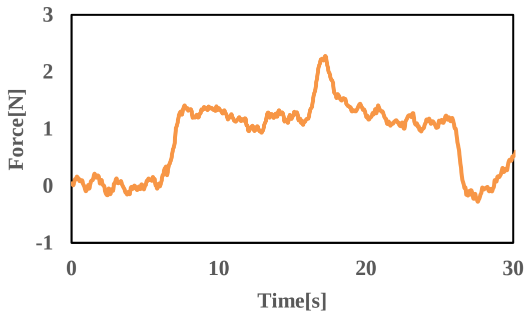

Figure 11 Force estimate result from type2 in X direction

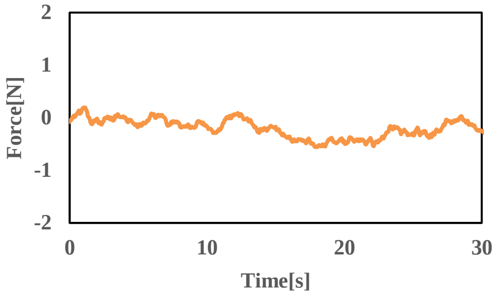

Figure 12 Force estimate result from type2 in Y direction

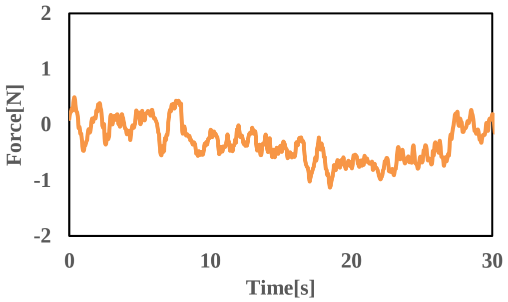

Figure 13 Force estimate result from type2 in Z direciton

5. Conclusions

The conclusions of this study are as follows

(1) Fluctuation of the torque of the drive shaft, which is believed to be caused by gravity, was found, and the external force estimation model was improved by removing the fluctuation.

(2) The external force estimation method was improved to extract only the effect of external force by removing the torque obtained from the current value, and only the component of change due to external force could be estimated.

(3) The force estimated by the external force estimation method (Type 2) is about 20 times smaller than the actual force, and possible causes are that the Jacobi matrix used does not include the geometrical error of mechanical elements and that the torque applied to each driven joint is ignored.

(4) Considering the real-time application incorporated in the digital twin, it is not possible to increase the input elements of the external force estimation model, so calibration using spindle torque is being considered.

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