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A Novel Haptic Display Based on Curvature Estimation and Its Application to a Machining Support Robot

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Abstract— **For finish processing of limited-production diversified products of complex shapes, the use of a bilaterally controlled robot is in some sense inevitable. However, a bilateral control system is very difficult to operate because a worker must be in constant contact with the slave tool. So, in this paper, we propose a method to show the shape of the workpiece from the estimated curvatures of its parts. In addition, we have built a support system for processing that is specifically adapted to the proposed method. The system consists of a 6-DOF parallel haptic device as the master robot and 4-DOF parallel robot as the slave robot. The effectiveness of the proposed method is demonstrated through three different experiments.**

I. INTRODUCTION

Automation by machines is progressing in the field of machining. Automated production methods require workpiece position and shape data to employ position control while performing a specific action upon it. Machine automation is more suited for mass production; since it takes a long time to reprogram production information, it is not suited for high-mix low-volume production. The finishing process for high-mix low-volume production is not automated and generally involves doing hand work. However, in the case of machining by hand, a worker has to change the feed rate and pressing force according to the situation while the processing situation is unclear, for instance, from the vibration of a drill. The work becomes even more difficult with the influence of disturbances such as tool rotation. The worker must work intensively, and inevitably makes processing mistakes in situations of prolonged work. In a previous study, the machining support device which performs debarring by estimating the tool's rotational effect using adaptive modeling is developed[1]. However, since a worker has the tool attached at the tip of the device, this system cannot make the accurate processing surface due to the device's bend. Thus, the field of finish-machining has long awaited the development of a processing support robot with bilateral control that does not require product data in advance.

Bilateral control is one type of master slave control. The master device, which is operated by a human, controls the movements of, a slave device located in a distant place while the slave device returns force data to the master device for the operator to sense. This control can present processed information of the slave device to the master device. The opposite is possible as well, and can remove disturbances such as tool rotation and hand movements. In addition, it is possible to do detailed processing work with the same sensations as usual while changing the location of the workspace. And because a worker doesn't have a tool, the problem of tool's stiffness is resolved and accurate positioning can be performed.

In a previous study of bilateral control, Ando et al. proposed a method of estimating the impedance of the contact object from the force and the position of the slave device in contact with the object. By changing the impedance with a contact object, they presented the hardness of the contact object and distinguished the contact object by its hardness[2].

In an attempt to apply bilateral control to the machining process, Kutomi et al. evaluated the ability of a proposed kinesthetic sense with PHANTOM1.5/6DOF manufactured by SensAble Technologies by which a haptic device and hydraulics convey a kinesthetic sense to the operator[3]. When performing finish machining by a haptic device or bilateral control such as theirs, a worker's applied force or the movement speed of a tool remains adaptable, in contrast to the case with automatic control, and the accuracy of the processing is still greatly dependent on the worker's skill level. In previous studies, a hybrid control method with position control and force control systems has been used[4]. However, these control methods cannot make the accurate processing surface due to the irregular change of feed speed or the irregular state of burrs. Osada et al developed a control method that changes the type of control depending on whether the slave device touched the object, such that during the machining, the motion of the slave robot against the normal direction of machining side is controlled absolutely by compliance control. They proposed a machining method while keeping the amount of cutting constant as expressed by the cutting power, the number of tool rotations, and the movement speed[5]. Although a worker operates the master device until a tool contact with a workpiece, after a tool contacts with a workpiece, the slave device operates independently. By showing the master side a virtual wall in the forcing direction, the processing accuracy is increased. However, it is difficult for a worker to operate the device freely while maintaining independent motion on the slave side.

When a bilateral control system is applied to the finish machining of complex shapes, it is very difficult to operate because the worker must be in constant contact with the

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slave tool. It becomes easier if the slave device fits the shape of workpiece by performing automatic force control, which takes inordinate effort to do manually. In this method, the master device presents a force against the normal direction based on the slave position. When force control is performed upon a circular component, the movement distance by force control increases more than the case in which straight-line processing is performed. As a result, if the processing is carried out based on the slave position, the presented force is easily destabilized. If the presented force becomes unstable, the system has the potential to burn up and the operability to become worse. With precision machining, the processing accuracy is raised by performing rate control, by which the speed is changed in a component-shaped concavo-convex part. When using bilateral control, because the feed rate of the tool is arbitrarily adjusted by the worker, it is necessary for the worker to change speed according to feedback the worker receives regarding the object's unevenness and to improve the processing accuracy. In addition, the works becomes difficult when the declination is resulted between the shape of workpiece obtained from worker's eye and the sense by reaction force presented from the master device. Therefore, it is thought that it is necessary to present the overall workpiece shape to the worker rather than simply present the force based on the slave position.

In order to present the workpiece shape to worker, it is necessary to estimate a curved form correctly. Thus, because a complicated-shaped workpiece can also be considered as a collection of parts of circles of various radii, in this research, we focus on concave and convex curvatures. Research focusing on the change of curve has been done in the field of end-mill processing of a plane cam with a continuous curve. Itou et al. worked on improving the processing accuracy in the corner part, paying attention to the change of the cutting depth by the change of curvature[6]. Ohtsuka et al. succeeded in improving the processing accuracy in the corner part by paying attention to the change in the ratio of cutting force value to the target cutting force[7]. However, these methods are difficult to apply to bilateral control because the tool path is set up in advance for research according to an automatic machine.

In this paper, we propose a method that estimates the curvature and presents the worker with the shape of the workpiece from the estimated curvature. Then, the proposed method is applied to a machining support robot. The machining support robot is shown in Fig.1. In order to always push a tool in the normal direction of the worked surface, it is necessary to with rotate the robot's wrist. The direction of the worked surface is estimated by the cutting force obtained from the force sensor, and the wrist of the slave device is rotated. The curvature of worked surface is estimated from the rotation angle of the wrist and the moving distance. The workpiece shape is obtained from the estimated curvature and presented to the worker using reaction force. With the application of the proposed method to a processing support robot, the tool can be machined while remaining in contact with the workpiece by operating the master device in accordance with the shape that the worker is able to recognize from the master device.

Fig. 1. Machining support robot

II. MACHINING SUPPORT SYSTEM

A. System summary

In this research, the delta haptic device manufactured by Force Dimension [8] was used as the master device and machining support robot developed in our laboratory was used as the slave device. Although there are some control methods for bilateral control, force-reflecting type bilateral control is standardized in this research because the delta devices do not have force sensors.

1) Specifications of the device: The delta.6 haptic device has a parallel link structure. It is possible to input both position and angle data for the 3 axes of the wrist. It is also possible to output the force data for 3 axes and the torque information for the direction of rotation of the wrist.

The slave device applies a rotating-type machine to the hand of 3-DOF parallel link manipulator, and the force sensor and the drill are attached to the wrist. A model of the slave device is shown in Fig.2. The base of the robot used in this study is a parallel link-type manipulator called DELTA with three legs; the robot's end effector can be moved horizontally without changing the robot's posture.

Table I lists the parameters of the arm(j=1) of the parallel link robot type DELTA. The coordinates of the arm(j=2) or arm(j=3) are the positions from the arm(j=1) $\frac{2}{3}\pi$ and $\frac{4}{3}\pi$ to the circumference of the Z-axis, respectively. Here, L_1 is the length of link 1, L_2 is the length of link 2, r_A is the distance from the center of the base to the joint, r_B is the distance from the center of the end effector to the joint, and $j(j$ = 1;2;3) is the angle formed between the X axis in the coordinate system and the vector directed toward the first joint of each link from the center of the base. The joint angles of the links are $1j$; $2j$; $3j(j$ = 1;2;3).

A parallel link manipulator using a servo motor (made by Fuji Electric Co.) with a gear reduction ratio of 20 is installed. The end effector uses a rotary actuator (made by Harmonic Drive systems inc.). Each specification is shown

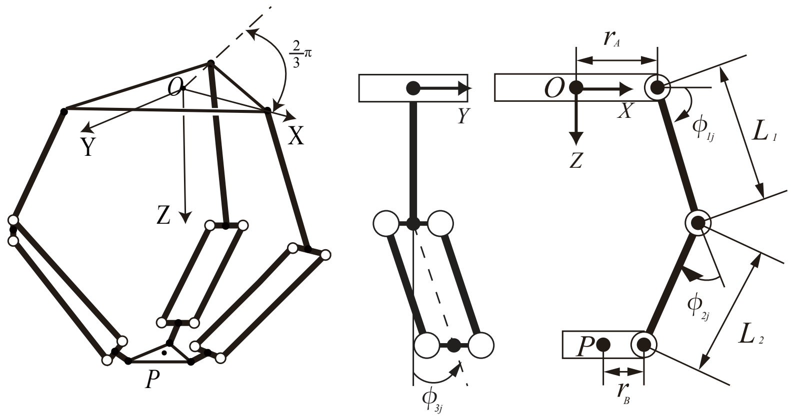

Fig. 2. Kinematic parameters of DELTA for arm (j=1)

TABLE I
KINEMATIC PARAMETERS

length of link1 L_1[mm]	200
length of link2 L_2[mm]	200
base size r_A[mm]	180
head size r_B[mm]	60
θ_j[rad]	$\frac{2\pi}{3} \times (j-1)$

TABLE IV
GRINDER SPECIFICATION

Grinder parts	KV11+H021+ET51
Unloaded revolution [rev/min]	5000 50000
Maximum torque [cN·m]	23
Power pack	C101A

in Table II and Table III. A 6-DOF force sensor is also installed in the end effector. Resolution of output voltage is 1/16834[V]. A Force is calculated by applying a calibration procession. The tool is a Minitor Co., Ltd. V11HS drill, which is a cemented carbide cutter (BC2022) of 3 mm in diameter. The drill's specification is shown in Table IV. The circlar portion of aluminum alloy ADC12 for aluminum-Si-Cu system diecastings was used for the workpiece in this research.This picture is shown in Fig.3.

Fig. 3. Workpiece in this research

TABLE II
MOTER SPECIFICATION FROM 1 AXIS TO 3 AXES

Moter model	GYS401DC1-SA
Moter driver	RYS401S3-VVX
Maximum stroll torque [N·m]	3.82
Maximum revolution [r/min]	5000
Encorder resolution [p/rev]	163840

TABLE III
MOTER SPECIFICATION OF 4 AXIS

Moter model	HFA-8C-100-E200
Moter driver	HA-655-1-200
Maximum stroll torque [N·m]	4.8
Maximum revolution [r/min]	60.0
Encorder resolution [p/rev]	800000

III. CONTROL SYSTEM DESIGN

A. Control system summary

We propose a control system to process a workpiece of complex shape using a machining support system with bilateral control. A model of the control law is shown in Fig.4. In this control law, first the rotation angle of the wrist is estimated from the cutting resistance obtained by the force sensor. The curvature radius is estimated from the estimated rotation angle and the moving distance. The shape of the workpiece is presented from the estimated curvature. The slave device is subjected to compliance control at the time of the cutting. In addition, it is possible that the declination occur between the master device position and the slave device position immediately after machining. Therefore, the deviation is lessened by approaching the slave device position to the master device position slowly. The presentation force of the master device doesn t exercise the power more than a constant value determined beforehand.

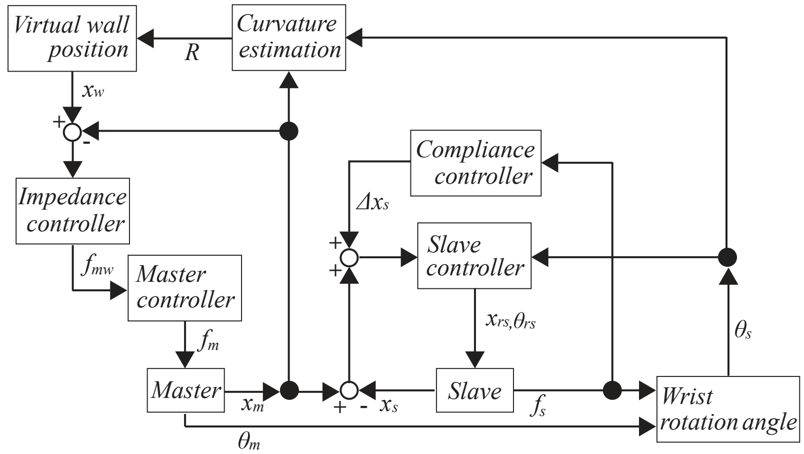

Fig. 4. Block diagram of proposal method

B. Estimation of the rotation angle

In order to process a curvilinear portion, it is necessary to rotate the wrist. However, when aimed at a strange-shaped processing part, the rotation angle of the wrist must be estimated and be rotated while processing because the rotation angle can't be inputted before.

Thus, we propose a method of estimating the rotation angle from the cutting resistance obtained by the force sensor. An overview of the cross section in the vertical tool axis is shown in Fig.5. When considering the cutting of a curve as in Fig.5, if the tool is moved flatly, the direction of cutting force is changed because the contact area of the workpiece and tool is changed. The rotation angle is estimated from the direction of the cutting force which changed.

From Fig.5,

$$\Delta\theta = \alpha_{i-1} - \alpha_i \tag{1}$$

based on the geometric relationship

$$\alpha = \arctan \frac{fy}{fx} \tag{2}$$

where $\Delta\theta$ is $\angle\, O_i'\mathrm{O}O_{i-1}'$, α is the angle to which the cutting force is applied, and f_x and f_y are the cutting forces of the x- and y-axis directions, respectively. From (1), (2), the following equation is obtained.

$$\Delta\theta = \arctan \frac{fy_{i-1}}{fx_{i-1}} - \arctan \frac{fy_i}{fx_i} \tag{3}$$

where $\Delta\theta$ is the rotation angle of wrist.

C. Estimation of the curvature

When a line is curved, the local curved condition can be approximated by a circle. This circle's radius is called the curvature radius and the reciprocal is called the curvature. Since the bending condition of a complicated-shaped workpiece can also be approximated to a circle, the shape of a complicated object can be expressed as an aggregate of the circle with various curvature radii. It also becomes possible

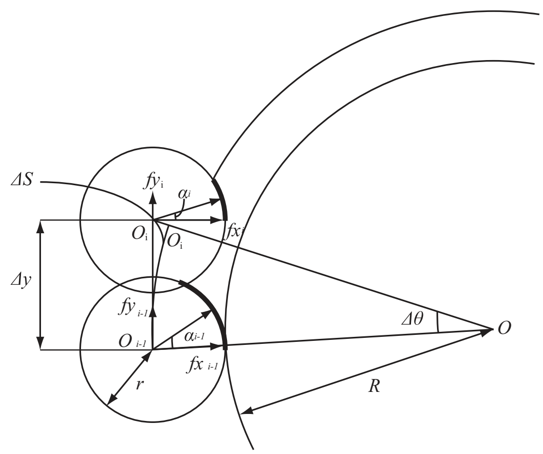

Fig. 5. Radius of curvature

to present a worker a complicated-shaped workpiece easily if the curvature radius or curvature can be estimated and it can be presented to the worker as part of circle.

We propose a method of estimating the curvature radius from the cutting resistance obtained by a force sensor. The curvature radius is estimated by dividing the movement distance by the rotation angle of the wrist, which is always estimated.

From Fig.5

$$\Delta S = (R + r) \times \Delta\theta \tag{4}$$

where ΔS is segment $O_i''O_{i-1}'$, R is curvature radius, r is tool radius. Then, from $\Delta\theta \ll 1$, we obtain $\Delta S \approx \Delta y$. Substituting (3) into (4),

$$R = \frac{\Delta y}{\Delta\theta} - r \tag{5}$$

Thus, the curvature radius is estimated from the cutting resistance obtained by force sensor.

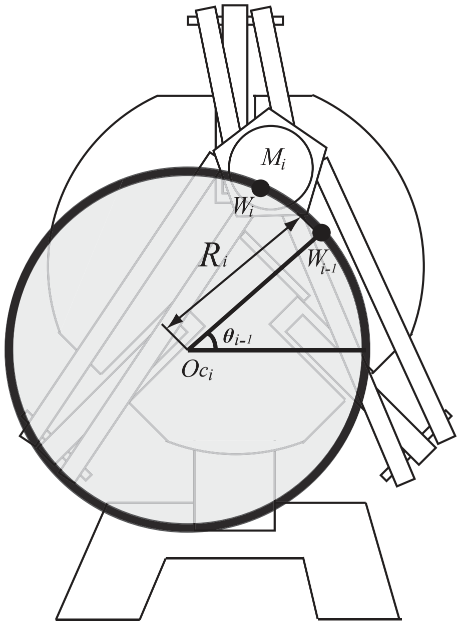

Fig. 6. Showing of the circle

D. Presentation method of shape

We proposed a presentation method for the estimated curvature radii. An example of a circle presented to the master device is shown in Fig.6, where $O_c(x_c,y_c)$ is the center of presented circle $M(x_m,y_m)$ is the position of the master $W(x_w,y_w)$ is the presentation position the of wall. Then,

$$x_{wi} = x_{ci} \pm R_i \cos(\arctan \frac{y_{mi} - y_{ci}}{x_{mi} - x_{ci}}) \tag{6}$$

$$y_{wi} = y_{ci} \pm R_i \sin(\arctan \frac{y_{mi} - y_{ci}}{x_{mi} - x_{ci}}) \tag{7}$$

where if x_m and y_m which are the position of master are positive, respectively, the double sign of (6) and (7) positive, and if x_m and y_m negative, respectively, the double sign is negative.

The center of the presented circle is obtained from the following equation:

$$x_{ci} = x_{wi-1} - R_i \cos \theta_{i-1} \tag{8}$$

$$y_{ci} = y_{wi-1} - R_i \sin \theta_{i-1} \tag{9}$$

It is possible to evaluate the position which presents reaction force by the rotation angle of the slave's wrist θ, and the estimated curvature radius R is substituted in (8), (9). The shape of the workpiece is presented to the worker by performing each calculation one by one and presenting reaction force at the coordinates obtained to the worker.

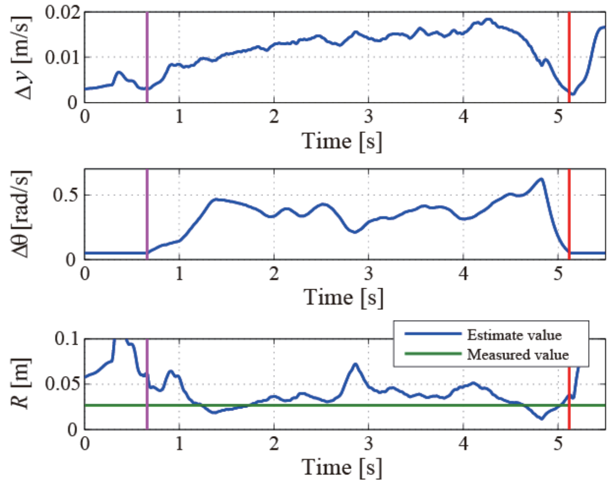

Fig. 7. Experimental result for each parameter

TABLE V
MACHINING DEPTH

	Average depth of machining [μm]	Machining depth difference [μm]
Case1	2100	3300
Case2	1300	1100
Case3	1300	700

IV. PROCESSING EXPERIMENT

In order to show the validity of this research, processing experiments for three difference patterns were conducted using Fig.3 as the workpiece. The first was a force presentation of the forcing direction to the master device without controlling the slave device in any particular way (Case 1). The second was a force presentation of the forcing direction to the master device with a particular control of particular to the slave device (Case 2). The third was a presentation of the shape based on the estimated curvature to the master device with a particular control of the slave device (Case 3). The first contact angle common to all the cases is made known, and is rotated with the directions by the side of a master to the value. The wrist is rotated according to the movement of the tool by the angle of rotation estimated by this proposed technique. Force presentation to the forcing direction was based on the position of the slave device [5].

A. Experimental result

The feed rate of the tool, the rotation angle of the wrist and the curvature radius for Case 3 using the proposed method are shown in Fig.7. The movement loci of the master and slave in each experiment are shown in Fig.8. The machining depth is shown in Fig.9. The average depth of machining and the machining depth average are listed in Table V.

B. Consideration

Regarding the estimation of the curvature radius, from Fig.7, although the curvature radius takes a large value at the start of machining and between 2.5[s] and 3.0[s], in the

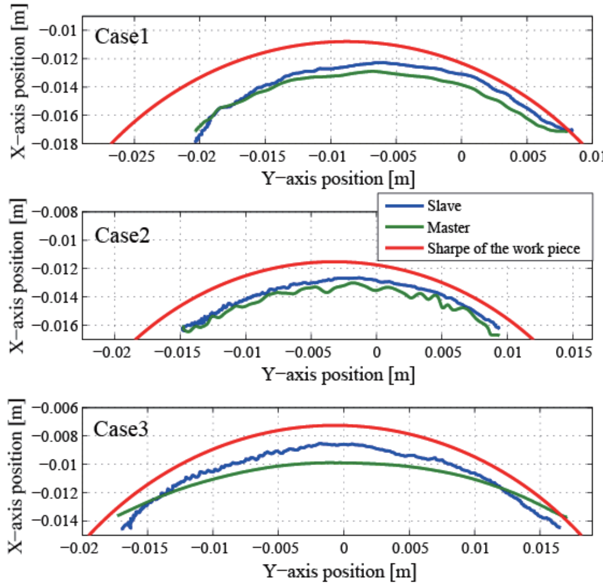

Fig. 8. Master and slave position

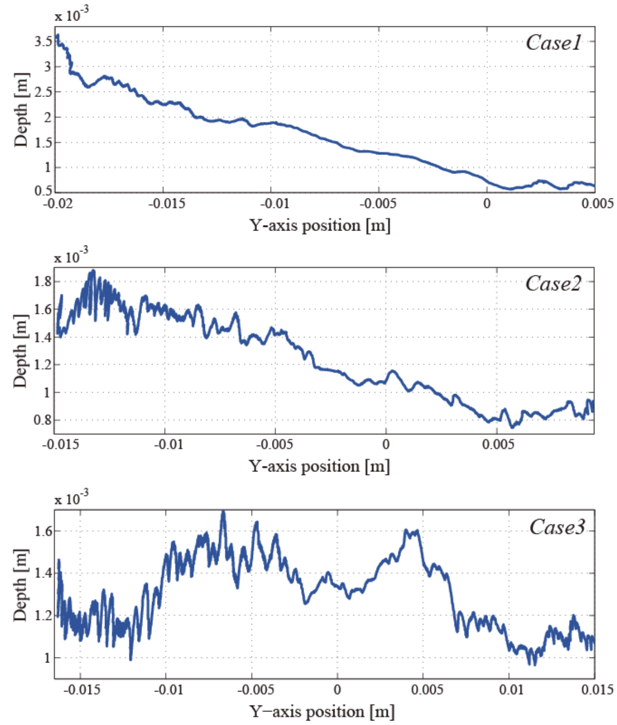

Fig. 9. Machining depth

other portions, it has a comparatively good value. Regarding the start of machining, the rotation of the wrist is delayed and I think that it has affected the estimation of the curvature radius. Between 2.5[s] and 3.0[s], when the tool passes through the peak of a circle, it is thought that since the contact area with the workpiece became small, the rotation angle also became small. Since it is thought that current system is still insufficient, it is necessary that a new system be added to stabilize the curvature radius.

Regarding the presentation of the workpiece shape, in Case2, the position of the master is unstable (Fig.9). As the master is always vibrating under machining operation, a gap between the shape seen by the eye and sensed by touch arose and it became hard to operate. Even gunder force control, since the master becomes unstable and the worker cannot adjust the sending speed well, the tool sinks into the workpiece and the processing accuracy deteriorates. In the proposed method, although the position of the master and the slave is not confirmed, since the moving direction of the slave device conforms to the master device, it was possible to work comfortably between the shape seen by the eye and the shape suggested by proposed method. If the directions where the master moves are in agreement even if the actual shape and presented shape are not in complete agreement, the worker can in fact process it comfortably.

Table V shows that the average depth of machining is no different between Case 2 and Case 3 while the machining depth difference of Case 3 is smaller. It can be said that Case 3 can be machined uniformly. It turns out that in Case 3, the tool can follow the shape of the workpiece using this proposed method.

V. CONCLUSION

In this research, the method of estimating the curvature radius from the cutting force and showing the worker the shape of the workpiece using the estimated curvature radius was proposed. The proposed method was adapted for a machining support robot. A processing experiment was conducted and it was shown that the worker can recognize the shape of the workpiece. The applicability of the proposed method is shown by conducting three kinds of experiments.

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