Design and Control of a Parallel Robot for Mold Polishing

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Abstract. A novel redundantly actuated parallel robot for mold polishing work is proposed. Cogging-less direct drive motors are implemented in the prototype. Instead of using conventional spherical sliding bearings, ball bearings with appropriate preload are implemented in the rolling pairs of the prototype. These mechanical parts enable fine force control for mold polishing work. The rated force of the robot perpendicular to the surface on the workpiece is 20 N with a tangential force of 5 N, which enable the robot to execute polishing tasks as well as skilled workers. In addition, the polishing velocity along the tangential direction is 60 m/min, which exceeds skilled workers' velocity of 10 m/min. High speed feed contributes to reducing the polishing force and improving the quality of the surface of the mold. Kinematics, statics, dynamics and control of redundantly actuated parallel robot are discussed in this paper. Impedance control was implemented to the prototype for stably executing the mold polishing work.

1 Introduction

In the mold polishing work, operator oscillates a stick type grinding stone on the surface of the work piece by hand at approximately speed of 10 m/min, with from 20 N to 30 N, up to 50 N contacting force. More than several hundreds of reciprocates oscillating is needed for fine finishing. There have been a lot of requests for automating this heavy work, and several researches for automating the mold polishing work using industrial robot manipulators[1-5]. Industrial robots are aimed not for force control but for position control. Frictions in the gear trains for enlarge the motor torque looses the back drivability and disturbs the fine force generation. Force feedback or mechanical floating devices has been tested for mold polishing by conventional industrial robot. However, industrial robot, consisted by serial mechanisms include heavy motors, has large effective mass at the tip, that disturbs high speed oscillating motion for mold polishing. Conventional researches polishing by industrial robot use rotating polishing tools for increasing the polishing speed. The characteristics of the finished surface by the rotating polishing tool is differs from that by the human operator using stick grinding stone by hand. Recently, high speed industrial robots, consisted by parallel mechanisms, have been commercially available [6,7]. Parallel robots have sufficient speed for the mold polishing tasks. However, these robots are not suitable when the robots contact their environment because almost all parallel robots are aimed not for force control but for position control.

In this paper, a novel redundantly actuated DALTA type [8] parallel robot aimed for force control is proposed. Kinematics, statics, dynamics, control and prototyping of

the parallel robot are discussed. Impedance control was implemented to the prototype for stably executing the mold polishing work.

2 Design of the parallel robot

2.1 Actuators

For the cogging-less fine force control, BLC09-25 by ShinMaywa Industries, Ltd., built in type slot-less direct drive motor with rated torque of 0.6 Nm, is selected. High resolution rotary encoder, Tonic by RENISHAW plc with 1,184,000 plus/rev was installed to the actuator. Instead of friction-full cross roller bearing, small friction deep groove ball bearings are installed around the motor. Appropriate pre pressure is applied to the bearings, for removing the clearances in the bearings. Developed actuator is shown in Fig. 1. Specifications of the actuator are summarized in Table 1.

2.2 Parallelogram linkages

Small friction parallelogram linkages with rotating pairs by ball bearings are designed for the robot. Small springs are installed in the rotating pairs for removing clearance, at the same time, for releasing unexpected force around the over constrained parallelogram linkage.

2.3 Design of the length of the arm

In order to gain the small torque of the slot-less motor, redundantly actuation of 4 motors for 3 dof parallel robot are adopted. Long arm enables high speed and large

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workspace of the robot, but at the same time, transmits small force to the moving plate. Length of the arm is designed in 50 mm for appropriate workspace and sufficient generative force and velocity at the moving plate (MP). Specification of the robot are summarized in Table 2. Schematic image of the mold polishing work by the robot and picture of the prototype are shown in Fig. 2.

Figure 1. Direct drive motor.

Table 1. Specifications of the actuator.

Rated torque	0.527 [Nm]
Peak torque	0.924 [Nm]
Rated speed	100 [min^{-1}]
Resolution	1,184k[p/rev]

Figure 2. Mold polishing robot.

Table 2. Specifications of the robot.

length of arm	50 [mm]
length of rod	200 [mm]
rated polishing force	20[N]
rated speed (XY)	60 [m/min]
work space (XY) (Z)	140×140[mm] 40[mm]

- O_b : Origin of the base plate(BP)
 O_m : Origin of the moving plate(MP)
 O_i : Position of the ith pair between the ith link and the BP
 A_i : Position of the ith pair between the ith link and the rod
 B_i : Position of the ith pair between the ith link and the MP
 r_{bi} : Radius of the BP
 r_{mi} : Radius of the MP
 φ_i : Angle of location of the ith pair on the MP
 $\mathbf{x}$: Position of the MP w.r.t. The BP coordinates
 $\mathbf{u}_i$: Unit direction vector of the arm
 r_i : length of the arm
 $\mathbf{v}_i$: Unit direction vector of the rod
 l_i : length of the rod
 θ_i : Angle of the motor
 $\mathbf{x}_i, \mathbf{y}_i$: Unit direction vectors perpendicular to the axis of the motor

Figure 3. Kinematic model of the robot.

3 Robot Control for Mold Polishing

3.1 Position Analysis

Kinematic model of the parallel robot is shown in Fig.3. There are two routes from O_i to B_i as shown in Eq. (1) and Eq. (2).

$$\overrightarrow{O_i B_i} = \overrightarrow{O_i O_b} + \overrightarrow{O_b O_m} + \overrightarrow{O_m B_i} = -r_{bi} \mathbf{s}_i + \mathbf{x} + r_{mi} \mathbf{s}_i$$

$$\mathbf{x} = [x \quad y \quad z]^T$$

$$\mathbf{s}_i = [\cos \varphi_i \quad \sin \varphi_i \quad 0]^T, i = 1, \dots, 4$$

$$\overrightarrow{O_i B_i} = \overrightarrow{O_i A_i} + \overrightarrow{A_i B_i} = r_i \mathbf{u}_i + l_i \mathbf{v}_i$$

$$\mathbf{u}_i = \cos \theta_i \mathbf{x}_i + \sin \theta_i \mathbf{y}_i$$

$$\mathbf{x}_i = [\cos \varphi_i \quad \sin \varphi_i \quad 0]^T$$

$$\mathbf{y}_i = [0 \quad 0 \quad 1]^T$$

By equation Eq. (1) and (2), one obtains loop closure equation that relates angle of the motor θ_i and position of the MP $\mathbf{x}$.

$$\mathbf{x} - (r_{bi} - r_{mi}) \mathbf{s}_i = r_i \mathbf{u}_i + l_i \mathbf{v}_i$$

3.2 Jacobian Matrices

Jacobian matrices $\mathbf{J}_x$ and $\mathbf{J}_q$ are given by differentiating both sides of Eq. (3) with respect to time as follows,

$$\mathbf{J}_x \dot{\mathbf{x}} = \mathbf{J}_q \dot{\mathbf{q}}$$

$$\begin{bmatrix} \mathbf{v}_1^T \\ \vdots \\ \mathbf{v}_4^T \end{bmatrix} \cdot \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} \mathbf{v}_1^T \mathbf{a}_1 & \dots & \mathbf{v}_1^T \mathbf{a}_4 \\ \vdots & \ddots & \vdots \\ \mathbf{v}_4^T \mathbf{a}_1 & \dots & \mathbf{v}_4^T \mathbf{a}_4 \end{bmatrix} \begin{bmatrix} r_1 \dot{\theta}_1 \\ \vdots \\ r_4 \dot{\theta}_4 \end{bmatrix}$$

$$\mathbf{a}_i = \frac{d\mathbf{u}_i}{d\theta_i} = -\sin \theta_i \mathbf{x}_i + \cos \theta_i \mathbf{y}_i$$

3.3 Statics

Relationship between the force $\mathbf{f}_x$ at the MP and the torques of the motors $\mathbf{f}_q$ is given as,

$$\mathbf{f}_x = \mathbf{J}^T \mathbf{f}_q$$

$$\mathbf{J} = \mathbf{J}_q^{-1} \mathbf{J}_x$$

$$\mathbf{f}_x = [f_x \quad f_y \quad f_z]^T$$

$$\mathbf{f}_q = [f_{q1} \quad \dots \quad f_{q4}]^T = \begin{bmatrix} \tau_1 / r_1 & \dots & \tau_4 / r_4 \end{bmatrix}^T$$

In Eq. (5), torque of each motor τ_i is converted to the generative force of the actuator f_{qi} which corresponds to the force at A_i to the direction of $\mathbf{a}_i$ in Eq. (4). In case of DELTA robot, the Jacobian matrix $\mathbf{J}_q$ becomes diagonal. Its inverse is also diagonal matrix, each element of $\mathbf{J}_q^{-1}$ is equal to the reciprocal of corresponding element of $\mathbf{J}_q$. Jacobian matrix $\mathbf{J}$ is given as the following simple form.

$$\mathbf{J} = \mathbf{J}_q^{-1} \mathbf{J}_x = \begin{bmatrix} \frac{\mathbf{v}_1}{\mathbf{v}_1^T \mathbf{a}_1} & \dots & \frac{\mathbf{v}_4}{\mathbf{v}_4^T \mathbf{a}_4} \end{bmatrix}$$

$$= [c_1 \quad \dots \quad c_4]$$

From the 1st equation of Eq. (5), actuator fore $\mathbf{f}_q$ is given as,

$$\mathbf{f}_q = (\mathbf{J}^T)^+ \mathbf{f}_x + \mathbf{s} \mathbf{f}_c \quad (7)$$

$(\mathbf{J}_T)^+$ represents pseudo-inverse of $\mathbf{J}^T$, $\mathbf{s}$ represents 4x1 projection vector which gives the orthogonal complement of $\mathbf{J}^T$, $\mathbf{f}_c$ is an arbitrary constant which gives amount of the internal force of redundantly actuation.

3.4 Impedance control

Mold polishing work by the robot is done by the impedance control[9,10]. Here, we derive the force-based impedance control of the redundantly actuated parallel robot. The equation of motion of the parallel robot can be rewritten as follows:

$$\mathbf{f} = \mathbf{M}(\mathbf{x})\ddot{\mathbf{x}} + \mathbf{h}(\mathbf{x}, \dot{\mathbf{x}}) + \mathbf{g}(\mathbf{x}) \quad (8)$$

The objective of impedance control is to control the dynamical behavior of the MP according to

$$\begin{aligned} \mathbf{f}_d &= \mathbf{M}_d \ddot{\mathbf{x}}_e + \mathbf{B}_d \dot{\mathbf{x}}_e + \mathbf{K}_d \mathbf{x}_e \\ \mathbf{x}_e &= \mathbf{x}_f - \mathbf{x} \end{aligned} \quad (9)$$

Vectors $\mathbf{x}_f$ and $\mathbf{x}$ are the reference trajectory and actual trajectory of the MP, respectively. $\mathbf{M}_d$, $\mathbf{B}_d$, and $\mathbf{K}_d$ are constant matrices that define the impedance characteristics of mass, damping, and stiffness, respectively. The actual position $\mathbf{x}$ are calculated via the forward kinematics from the positions of actuators. The force command $\mathbf{f}_e$ that can yield the desired impedance at the MP is expressed as follows:

$$\mathbf{f}_e = \mathbf{f}_d + \hat{\mathbf{M}}(\mathbf{x})\ddot{\mathbf{x}} + \hat{\mathbf{h}}(\mathbf{x}, \dot{\mathbf{x}}) + \hat{\mathbf{g}}(\mathbf{x}) \quad (10)$$

the where $\hat{\mathbf{M}}$, $\hat{\mathbf{h}}$, and $\hat{\mathbf{g}}$ are the nominal values of $\mathbf{M}$, $\mathbf{h}$, and $\mathbf{g}$, respectively. The force command for the actuators is given by (7) as follows:

$$\mathbf{f}_q = (\mathbf{J}^T)^+ \mathbf{f}_e + \mathbf{s} \mathbf{f}_c \quad (11)$$

4 Experiments

4.1 Experimental Setup

Polishing stone is attached at the MP via 3 axes force sensor. Hexapod, 6 dof Stewart platform parallel robot, and rotary table are prepared for tilting, panning and rotating the work piece. iBIS by MTT Corp., DSP based real time controller equipped with D/A, A/D, PiO and counter, is used for control the mold polishing parallel robot. A model based control software was developed by Simulink. iBIS can communicate to the host computer during executing the polishing work, positions, velocities, accelerations and forces are monitored and stored to the host computer. In addition, polishing parameter, such as desired trajectory, velocity, impedance, polishing force, etc, can be changed during executing the polishing work. Control system of the mold polishing robot is shown in Fig. 4. Experimental setup of the mold polishing is shown in Fig. 5.

4.2 Mold Polishing by Robot System

Mold polishing work was executed by the parallel robot. For the first test, flat surface was polished with polishing speed of 10 m/min (same velocity as human operator), and 20 m/min as shown in Fig. 6 (a). Actual polishing force and velocity were monitored by the host computer as shown in Fig. 6 (b). Movie of the test is uploaded to our website [11].

Figure 4. Control system of the mold polishing robot.

Figure 5. Experimental setup of the mold polishing.

(a) polishing tool and workpiece

(b) monitoring the polishing work

Figure 6. Experimental setup of the mold polishing.

robot were discussed in this paper. Impedance control was implemented to the prototype for stably executing the mold polishing work. Optimizing the polishing conditions and polishing of the curved surface are our future researches.

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5 Summary

A novel redundantly actuated parallel robot for mold polishing work was proposed. Kinematics, statics, dynamics and control of redundantly actuated parallel