Intelligent Desktop NC Machine Tool with Compliant Motion Capability

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Abstract

In this paper, a new desktop NC machine tool with compliance control capability is presented for finishing metallic molds with small curved surface. The NC machine tool consists of four single-axis robots. Tools attached to the tip of the z-axis are ball-end abrasive tools. The control system of the NC machine tool is composed of a force feedback loop, position feedback loop and position feed-forward loop. The force feedback loop controls the polishing force consisting of tool contact force and kinetic friction force. The position feedback loop controls the position in pick feed direction. Further, the position feed-forward loop leads the tool tip along cutter location data. In order to first confirm the application limit of a conventional industrial robot to a finishing task, we evaluate the backlash that causes the position inaccuracy at the tip of an abrasive tool, through a simple position/force measurement. Through a similar measurement and a surface following control experiment along a lens mold, the basic position/force controllability with high resolutions is demonstrated.

1 Introduction

In this paper, a new desktop NC machine tool with compliance control capability is presented for finishing metallic molds with small curved surface. The NC machine tool consists of four single-axis robots. Tools attached to the tip of the z-axis are ball-end abrasive tools. The control system of the NC machine tool is composed of a force feedback loop, position feedback loop and position feed-forward loop [1]. The force feedback loop controls the polishing force consisting of tool contact force and kinetic friction force. The position feedback loop controls the position in pick feed direction. Further, the position feed-forward loop leads the tool tip along cutter location data. It is expected that the NC machine tool delicately removes surface cusps with under about 0.3 mm height on a mold, and finishes the surface with high quality. In order to first confirm the application limit of a conventional industrial robot to a finishing task, we evaluate the backlash that causes the position inaccuracy at the tip of the abrasive tool, through a simple position/force measurement. Through a similar measurement and a surface following control experiment along a lens mold, the basic position/force controllability of the proposed NC machine tool is demonstrated.

2 Limitation of an Industrial Robot

In this section, effective stiffness, valid position resolution of Cartesian-based servo system and force resolution in a finishing system based on an industrial robot are evaluated. The effective stiffness means the total stiffness including the characteristics composed of an industrial robot itself, force sensor, attachment, abrasive tool, workpiece, zig and floor. The industrial robot used is the MOTOMAN-UP6. A 6-DOF compact force sensor is attached to the arm tip, and a ball-end abrasive tool is fixed to the tip through a servo spindle.

Figure 1 shows the relation between the position and contact force obtained by a simple contact experiment. The quantity of the position is the z-directional component at the tip of an abrasive tool, which is calculated by the forward kinematics using the joint angles obtained from the inner encoders. The quantity of force is yielded by contacting the tool tip with a workpiece and is measured by the force sensor. When the tool tip contacts to a workpiece, small manipulated variables under 0.01 mm could not cause any effective force measurements, so that we conducted the experiment while giving the minimum resolution -0.01 mm in press motion and 0.01 mm in unpress motion.

In the experiment, the tool tip approached to an aluminum workpiece with a low speed, and after touching the workpiece, i.e., after detecting a contact force, the tool tip was pressed against the workpiece with every 0.01 mm. The graph written with black squares in Fig. 1 shows the relation the position and contact force. The force is about 36 N when the position of the tool tip is -0.3 mm, so that the effective stiffness within the range can be estimated with 120 N/mm. After the contact motion, the tool tip was

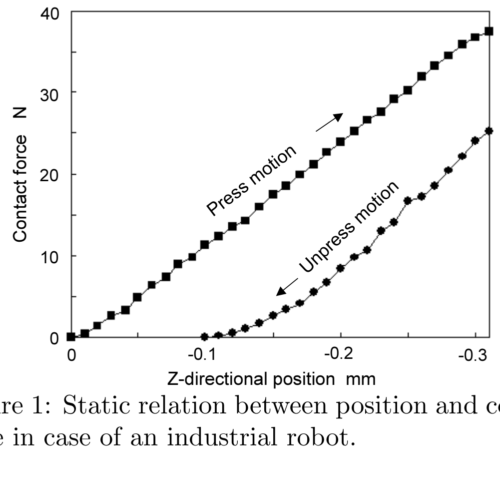

Figure 1: Static relation between position and contact force in case of an industrial robot.

away from the workpiece once, and returned to the position again where 36 N had been obtained. After that, the tool tip was unpressed every 0.01 mm. The graph written with ● shows the relation of the position and contact force of this case. It is observed from the results that there exists a large backlash about 0.1 mm. This value is almost the same compared to the general one that is guaranteed as repetitive position accuracy of articulated industrial robots. That is the reason why in order to design a polishing system using an industrial robot we must consider a force control system with the force resolution 1.2 N under the position uncertainty 0.1 mm.

3 NC Machine Tool with Compliance

Figure 2 shows the developed NC machine tool consisting of four single-axis robots with a position resolution of 1 m. The size of the machine tool is 850 × 645 × 700 mm. The single axis-robot is a position control device ISPA with high-precision resolution provided by IAI Corp., which is composed of a base, linear guide, ball-screw, AC servo motor. The effective strokes in x-, y- and z-directions are respectively 400, 300 and 100 mm. To regulate the tool revolution, the robot used in z-direction has a spindle motor between the tool and force sensor.

The hardware block diagram is shown in Fig. 3. Figure 4 shows the static relation between position and contact force in case of the proposed NC machine tool with a ball-end abrasive tool. The experiment was conducted in the same condition as shown in Fig. 1. It is observed that the undesirable backlash is largely decreased and the effective stiffness is about 30/0.2=150 N/mm. On the other hand, Figure 5 shows the relation in case that a ball-end elastic abrasive tool is used. It is observed that the effective stiffness changes down to about 30/0.36≒83.3 N/mm according to the property of the elastic abrasive tool. As can be seen, the effective stiffness of force control system is largely affected by the kinds of the abrasive tool used. In the case of the elastic abrasive tool called a rubber abrasive tool, the force resolution about 0.083 N can be performed due to the position resolution of 1 m.

4 Weak Coupling Control

The tool tip is controlled by the translational velocity given by

$$^W\boldsymbol{v}(k) = {^W\boldsymbol{v}_t(k)} + {^W\boldsymbol{v}_n(k)} + {^W\boldsymbol{v}_p(k)} \quad (1)$$

where k denotes the discrete time; superscript ^{W} denotes the work coordinate system. It is assumed that the polishing force is the resultant force of the contact force and friction force, and also is obtained as the resultant force of x-, y- and z-directional force sensor measurements. Figure 6 shows the proposed block diagram of the CL data-based hybrid position/force controller with weak coupling. First of all, $^W\boldsymbol{v}_t(k)$ is the manipulated variable generated from the feedforward control law based on CL data. $^W\boldsymbol{v}_t(k)$ is the

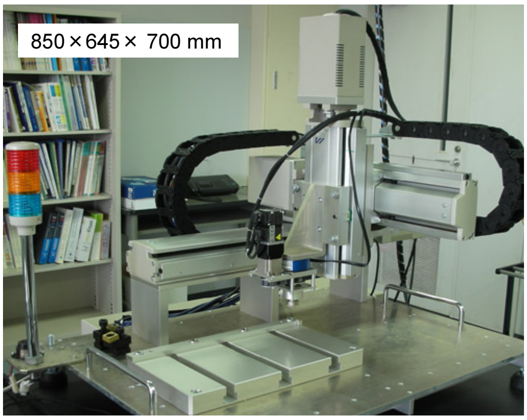

Figure 2: Proposed NC machine tool with compliance.

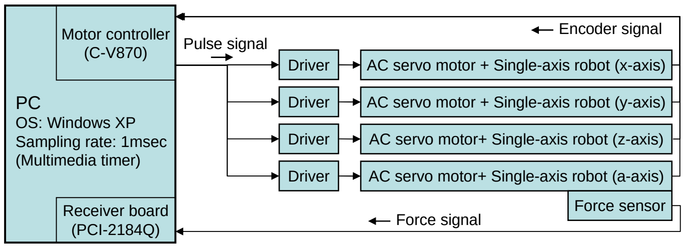

Figure 3: Hardware block diagram of the proposed NC machine tool composed of four single-axis robots.

tangential velocity and written by

$$^W\boldsymbol{v}_t(k) = v_{tangent}(k)\frac{^W\boldsymbol{t}(k)}{\|^W\boldsymbol{t}(k)\|} \quad (2)$$

where $v_{tangent}(k)$ is a velocity norm. $^W\boldsymbol{t}(k)$ is the tangential vector calculated by using the CL data. Also, $^W\boldsymbol{v}_n(k)$ is the manipulated variable generated from the force feedback control law. $^W\boldsymbol{v}_n(k)$ is the normal velocity written by

$$^W\boldsymbol{v}_n(k) = v_{normal}(k)\,^W\boldsymbol{o}_d(k) \quad (3)$$

where $^W\boldsymbol{o}_d(k)$ is the normal vector calculated using the direction components of CL data. The scalar $v_{normal}(k)$ representing the normal velocity is the output of the impedance model following force control law given by

$$v_{normal}(k) = v_{normal}(k-1)\; e^{-\frac{B_d}{M_d}\Delta t} + \left(e^{-\frac{B_d}{M_d}\Delta t} - 1\right)\frac{K_f}{B_d}E_f(k) \quad (4)$$

where K_f is the force feedback gain, and impedance parameters M_d and B_d are the desired mass and damping coefficients, respectively. Δt is the sampling time. $E_f(k)$ is the error between the desired polishing force F_d and norm of force $^S\boldsymbol{F}(k) \in \Re^3$ measure by the force sensor, which is given by

$$E_f(k) = F_d - \|^S\boldsymbol{F}(k)\| \quad (5)$$

where superscript ^{S} represents the sensor coordinate system. Also, $^W\boldsymbol{v}_p(k)$ is the manipulated variable

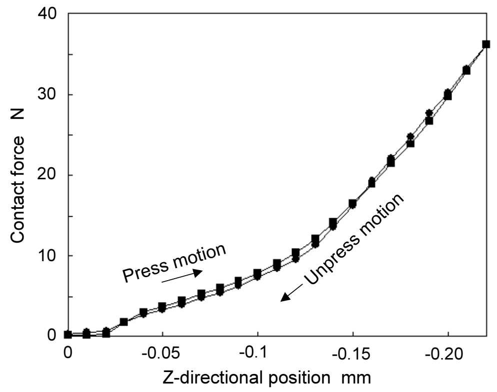

Figure 4: Static relation between position and contact force in case of the proposed NC machine tool with a ball-end abrasive tool.

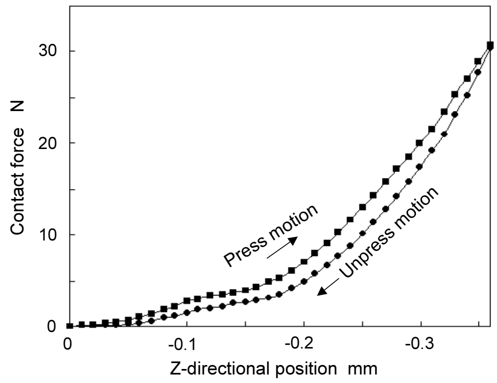

Figure 5: Static relation between position and contact force in case of the proposed NC machine tool with a ball-end elastic abrasive tool.

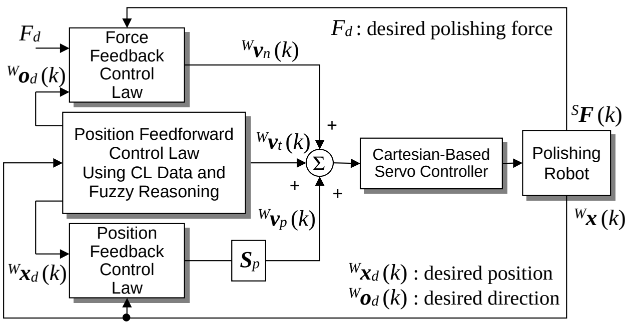

Figure 6: Block diagram of the CL data-based hybrid position/force controller with weak coupling.

yielded by a position feedback control law given by

$$^{W}\boldsymbol{v}_p(k) = \boldsymbol{S}_p\Big\{\boldsymbol{K}_p\boldsymbol{E}_p(k) + \boldsymbol{K}_i\sum_{n=1}^{k}\boldsymbol{E}_p(n)\Big\} \tag{6}$$

where the switch matrix $\boldsymbol{S}_p = \mathrm{diag}(S_x, S_y, S_z)$ makes the weak coupling control to force control direction active or inactive; $\boldsymbol{E}_p(k) = {}^{W}\boldsymbol{x}_d(k) - {}^{W}\boldsymbol{x}(k)$ is the position error. The desired position ${}^{W}\boldsymbol{x}_d(k)$ is calculated using CL data. $\boldsymbol{K}_p = \mathrm{diag}(K_{px}, K_{py}, K_{pz})$ and $\boldsymbol{K}_i = \mathrm{diag}(K_{ix}, K_{iy}, K_{iz})$ are proportional and integral gains for position feedback control.

Next, a desired damping tuning method using the effective stiffness of the NC machine tool is proposed considering the critical damping condition. When the

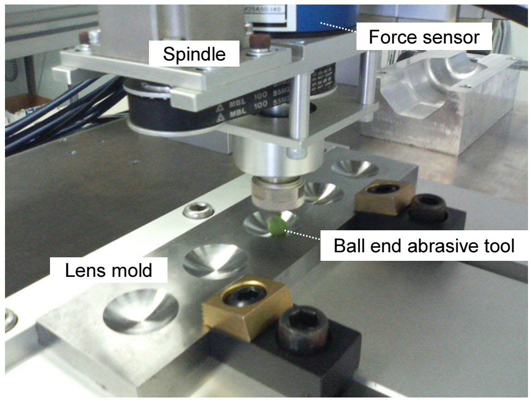

Figure 7: Profiling control scene along a spiral path.

polishing force is controlled, the characteristics of force control system can be varied according to the combination of impedance parameters such as the desired mass and damping. In order to increase the force control stability the desired damping, which has much influence on force control stability, should be tuned suitably. Eq. (4) is derived from the following impedance model.

$$M_d(\ddot{x} - \ddot{x}_d) + B_d(\dot{x} - \dot{x}_d) = K_f(F - F_d) \tag{7}$$

where $\ddot{x}$, $\dot{x}$ and F are the acceleration, velocity and force scalars in the direction of force control, respectively. $\ddot{x}_d$, $\dot{x}_d$ and F_d are the desired acceleration, velocity and force, respectively. When the force control is active, $\ddot{x}_d$ and $\dot{x}_d$ are set to zero. It is assumed that F is the external force given by the environment and is model as

$$F = -B_m\dot{x} - K_m x \tag{8}$$

where B_m and K_m are the viscosity and stiffness coefficients of the environment, respectively. Eqs. (7) and (8) lead to the following second order lag system.

$$\ddot{x} + \frac{B_d - K_f B_m}{M_d}\dot{x} + \frac{K_f K_m}{M_d}x = 0 \tag{9}$$

The critical damping condition of Eq. (9) leads to

$$B_d = 2\sqrt{M_d K_f K_m} - K_f B_m \tag{10}$$

The base value for the desired damping is calculated with Eq. (10).

5 Experiment

In this section, the fundamental performance of the proposed NC machine tool is evaluated with respect to force control and position control. A profiling control experiment is conducted by using a plastic lens mold after NC machining as shown in Fig. 7. The target mold is regularly machined with the forms whose diameter and depth under the partition line are 30 mm and 5 mm, respectively. At the start of the experiment, a small ball-end elastic abrasive tool approaches to the center of machined part with 2 mm/s. After detecting 5 N, which is 1/2 of the desired polishing force

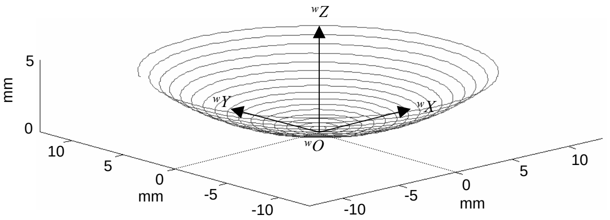

Figure 8: Position control result along the spiral path.

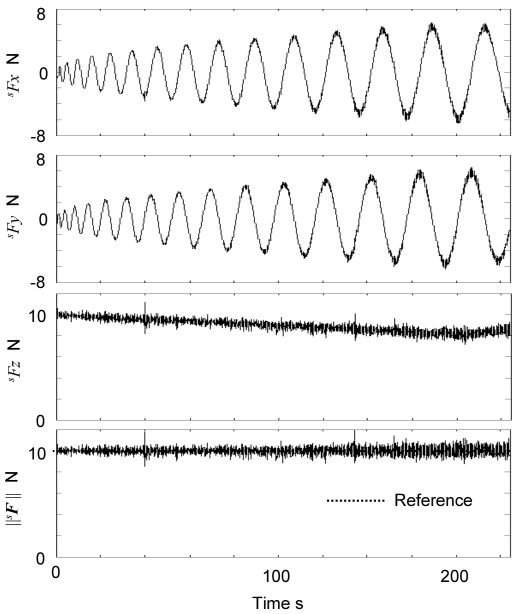

Figure 9: Control result of the polishing force $\|{}^S\boldsymbol{F}(k)\|$.

10 N, the tool tip starts to follow a spiral path. The effective stiffness K_m is estimated 30/0.36≒83.3 N/mm in case of the ball-end elastic abrasive tool. The desired mass M_d and force feedback gain K_f are set to 0.01, respectively. Also, it is assumed that $K_f B_m$≒0 since the viscosity of the force control system is considerably small. Accordingly, Eq. (10) leads to B_d=0.183 N·s/mm.

Next, control systems in x-,y- and z-directions are explained. The polishing force and z-directional position are regulated by feedback control laws and also x- and y-directional positions are feedforwardly controlled based on CL data. The CL data, that are desired trajectory, forms a spiral path with 0.8 mm pitch in x-y plane. Figure 8 shows the position control result, in which the pitch in x-y plane at the height 4 mm becomes about 0.7 mm. This is caused by that the manipulated variable from the force feedback control law gradually yields in x- and y- directions when the tool goes up along the spiral path. In other words, the reason is that only z-direction is designed with a position closed loop, the positions in x- and y-directions are corrected by the manipulated variable of the force control system, i.e., by the constraint of the force control system. Also, z-directional position was designed with a weak closed loop by using a small gain 0.001, so that a weak coupling was conducted against to the force feedback loop. In spite of such a situation, the mean error of z-directional position was about 2.7 m. The mean error of z-directional position is obtained by

$$E_{Pz} = \frac{\sum_{n=1}^{N} \sqrt{\left[{}^W x_{dz}(n) - {}^W x_z(k)\right]^2}}{N} \tag{11}$$

where N is the total step number in CL data, i.e., the number of 'GOTO' statement. ${}^W x_{dz}(n)$ is the z-directional component at the n step in CL data, ${}^W x_z(k)$ is the z-directional position at the tool tip obtained from an encoder. k is the discrete time when the ${}^W x_{dz}(n)$ is set.

Figure 9 illustrates the control result of the polishing force. The upper, second and third figures show x-,y- and z-directional forces in sensor coordinate system, respectively. The lower figure shows the norm $\|{}^S\boldsymbol{F}\|$. It is observed from the ${}^S F_x$ and ${}^S F_y$ that the direction of force control frequently varies due to the position control along the spiral path. Also, although the force measurements in x- and y-directions increase with the rise of the tool and the z-directional force one decreased gradually, it can be confirmed that the $\|{}^S\boldsymbol{F}\|$ could satisfactorily follow the reference value 10 N.

6 Conclusions

In this paper, we have first examined the resolution of position and force, and effective stiffness through an experiment using an articulated 6-DOF industrial robot. Also, technical points to be improved have been considered to develop a new finishing system which can be applied to small workpieces with curved surface. Next, a Cartesian-Type robot with a position resolution of 1 m and force resolution of 0.083 N has been designed by combining single-axis robots. A hybrid position and force controller with compliance controllability has been also proposed for finishing task, in which position control, force control or their weak coupling control can be selected according to each finishing strategy.

Further, we have introduced a systematic tuning method of the desired damping which is calculated from the critically damped condition using the static relation between the position and force at the tool tip. Finally, a profiling control experiment of a plastic lens mold with axis symmetric surface has been conducted along a spiral path to evaluate the characteristics of position and force control. Consequently, it has been confirmed that the proposed NC machine tool has a desirable control performance of position and force which would be applied to the finishing task of plastic lens molds.

References

[1] F. Nagata, T. Hase, Z. Haga, M. Omoto, and K. Watanabe, CAD/CAM-based position/force controller for a mold polishing robot, Mechatronics, 17 (4-5), pp. 207–216, 2007.