Polishing Robot for PET Bottle Molds  
Using a Learning-Based Hybrid Position/Force Controller

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Abstract

In this paper, a high precision polishing robot with a learning-based hybrid position/force controller is proposed for polishing PET (Poly Ethylene Terephthalate) bottle molds. In polishing, the position control system loosely interferes with the force control system in suitable directions. The shape of a mounted abrasive tool, attached to the tip of a robot arm, is a ball-end type. When a PET bottle mold with curved surface is polished, not only the orientation of the mounted abrasive tool is fixed but also its revolution is locked. The motion of the mounted abrasive tool is feedforwardly controlled based on an initial trajectory calculated in advance. The trajectory is generated from cutter location data constituted from a CAM system. The trajectory is modified through the actual polishing processes so that the total force error in polishing becomes smaller. The surface is polished by a polishing force acting between the mold and the abrasive tool. The polishing force is assumed to be considered as a composite force of the contact and kinetic friction forces, in which the friction consists of Coulomb and viscous frictions. A few polishing experiments are conducted to show that the proposed system is effective for obtaining a polishing surface as achieved by skilled workers.

1 Introduction

A 3D polishing robot has been already proposed for the manufacturing industry of attractively designed furniture [1-3]. The polishing robot was developed based on an open architectural industrial robot, where the kinematics and servo control are opened. At the next stage, we are now trying to apply the robot to the polishing of PET bottle molds. In the manufacturing industry of PET bottle molds, 3D CAD/CAM systems and NC machine tools are being used generally and widely, and these advanced systems have drastically rationalized the design and manufacturing process of the mold. However, the polishing process after NC machining has hardly automated yet. Although several polishing robots, in which force control techniques are applied, have been proposed, they are not introduced in manufacturing industry due to the poor polishing quality and complicated teaching. Consequently we must depend on skilled workers who can carry out both dexterous force control and skillful trajectory control for an abrasive tool as shown in Fig. 1. The skilled workers usually use mounted abrasive tools with ball-end shape. In using these types of tools, keeping
contact with a metallic workpiece with a desired polishing force and a tangential velocity is the most important to obtain a high quality finishing of the surface. Furthermore, when conducting a polishing task, it should be also noted that skilled workers move the polishing tool back and force along the object surface.

Generally, since the repetitive position accuracy at the tip of industrial robots is 0.1 [mm] or its neighborhood, it is so difficult to polish the surface of a metallic mold only using a position control strategy. In the polishing process of the metallic surface, the accuracy of 50 [nm] or less is finally required for mirror finishing. Especially, when a robot contacts to an object, several factors that decrease the total stiffness of the system are included. They are called a clearance, strain and deflection, all of which exist in not only the robot itself but also force sensor, abrasive tool and so on. Therefore, it is meaningless to discuss the position accuracy of the abrasive tool attached to the tip of the robot arm. If a position control only is used to a polishing task in which an abrasive tool and an object contact to each other, then both the stiffness of the robot itself and the total stiffness including the abrasive tool must be extremely high.

Up to now, several papers have described that a force control strategy is indispensable to realize any polishing robots [4-7]. However, the mere using of the force control method can’t achieve a smooth mirror finish required. This is the reason why no advanced polishing robots have been successfully produced on a commercial basis for metallic molds with curved surface. In this paper, a learning-based hybrid position/force control method is proposed for the polishing of PET bottle molds, and further it is applied to an actual polishing robot. In polishing, the position control system loosely interferes with the force control system to realize both accurate pick feed control and stable force control in suitable directions. In other words, the polishing robot can follow the curved surface along a desired trajectory monitoring the polishing force. The polishing force is assumed to be considered as a composite force of contact and kinetic friction forces, in which the friction consists of Coulomb and viscous frictions. Velocities in the normal and tangent directions are delicately controlled so that the polishing force can track the desired value. The effectiveness and promise of the proposed method are proved through a few experiments using an industrial robot MOTOMAN UP-6 with an open programming interface.

2 Polishing Strategy Considering Friction Forces

In this section, a polishing system based on an open architectural industrial robot is described in detail. The proposed system is illustrated in Fig. 2, in which a mounted abrasive tool is attached to the tip of a 6-DOF articulated robot through a 3-DOF force sensor. The mounted abrasive tool is generally attached to electrically driven tools, so that the polishing power can be obtained by its rotational motion. On the other hand, in order to avoid undesirable over-polishing, the proposed system keeps the rotation of the tool fixed, and polishes the workpiece using the resultant force \( \mathbf{F}_r \) of the Coulomb friction force \( \sum \mathbf{f}_{\text{Coulomb}} - \mathbf{f}_{\text{viscous}} \) and the viscous friction force \( \sum \mathbf{f}_{\text{viscous}} \). Here, \( \mathbf{f}_{\text{Coulomb}} \) and \( \mathbf{f}_{\text{viscous}} \) are the forces resulting from Coulomb friction and viscous friction, respectively. Each friction is yielded by a contact force \( \mathbf{f} = [f_n, f_t, f_c] \) [kgf] and tangent directional velocity \( v_t = [v_{tn}, v_{tt}, v_{tc}] \) [mm/s], respectively. It is emphasized that locking the motion of the mounted abrasive tool is effective for suppressing the over-polishing.

Figure 3 shows the control strategy considering the friction forces. The polishing force is given by the normal velocity \( \mathbf{v}_n = [v_{tn}, v_{nn}, v_{nc}] \) [mm/s] at the contact point between the abrasive tool and the workpiece. In this paper, the polishing force is defined as the resultant force of \( \mathbf{F}_r \) and \( \mathbf{f} \). Then, in order to avoid the
interference between the tool and the workpiece, the orientation of the tool is not changed and fixed to z-axis in base coordinate system. Fortunately, the molds for PET bottles have no overhangs. The polishing is performed by the hybrid control of the translational motion and the polishing force. The proposed system need not use complex tools and jigs, so that it can be simply realized.

3 Learning-Based Hybrid Position/Force Controller with Loose Interference

3.1 Feedback Control of Polishing Force

In polishing, it is assumed that the friction force \( F_f \), acting on the abrasive tool is mainly composed of Coulomb and viscous frictions. Thus, \( F_f \) is represented by

\[
F_f(k) = -\text{diag} \left( \mu_x, \mu_y, \mu_z \right) f(k) \left[ \frac{v_x(k)}{v(k)} \right] - \text{diag} \left( \eta_x, \eta_y, \eta_z \right) v(k) \tag{1}
\]

where \( k \) denotes the discrete time. The polishing force is obtained as the resultant force of the contact force \( f(k) \) in normal direction and the kinetic friction force \( F_f(k) \) in tangent direction. The force vector \( F(k) \) measured by the force sensor as shown in Fig. 4 is regarded as the polishing force, so that it can be written by

\[
F(k) = f(k) + F_f(k) \tag{2}
\]

In the proposed polishing robot, the polishing force is controlled by the impedance model following force control method [8, 9] given by

\[
v_x(k) = e^{-M_{x\cdot}B_{x\cdot}K_{x\cdot}(k-1)} - \left( e^{-M_{x\cdot}B_{x\cdot}K_{x\cdot}(k-1)} I_K K_f \right) \{ F(k) - F^* \} \tag{3}
\]

where \( M_x = \text{diag}(M_{x\cdot}, M_{y\cdot}, M_{z\cdot}) \), \( B_x = \text{diag}(B_{x\cdot}, B_{y\cdot}, B_{z\cdot}) \) and \( K_f = \text{diag}(K_{x\cdot}, K_{y\cdot}, K_{z\cdot}) \) are the desired mass, desired damping and force feedback gain matrices, respectively. \( F^* \) and \( K_f \) are set as the positive definite diagonal matrices. \( F = [F_{x\cdot}, F_{y\cdot}, F_{z\cdot}]^T \) is the desired polishing force, \( \Delta t \) and \( I \) are the sampling width and identity matrix, respectively.

3.2 Feedforward Position Control of Mounted Abrasive Tools

Currently, almost all molds for PET bottle manufacturing are designed and machined with 3D CAD/CAM systems and machining centers; accordingly cutter location data (CL data) generated from the main processor of CAM can be used for the desired trajectory of the mounted abrasive tool. The CL data, which are beforehand calculated based on a zigzag path or a whirl path, are the basic trajectory at the tip of the abrasive tool as shown in Fig. 5. The \( n \)-th step \( T(n) \in \mathbb{R}^6 \) of the CL data is composed of a position and orientation vector. The mainprocessor of CAM usually generates the CL data with linear approximation. Therefore, the desired position and orientation vector \( r(k) = [x(k), o(k)] \) at the discrete time \( k \) is calculated through a linear equation. The generation image of the \( r(k) \) is shown in Fig. 6. The explicit equation to calculate the \( r(k) \) is described in [1, 9]. The motion of the abrasive tool is feedforwardly controlled by a tangent directional velocity \( v_x(k) \) calculated from \( r(k) \) and a given velocity norm. On the other hand, when the polishing force is controlled by Eq. (3), \( v_x(k) \) is given to normal to the surface, i.e., perpendicular to \( v_x(k) \).
3.3 Extraction of the CL data

As mentioned above, the CL data are used for the initial trajectory of the mounted abrasive tool. For example, a trajectory for a polishing experiment is illustrated in Fig. 5. In this case, a zigzag path with a pick feed (0.2 [mm]) is specified. Therefore, the main-processor of the CAM generates a path so that the mounted abrasive tool can move with a reciprocating motion along the curved surface, i.e., (1) → (2) → (3) → (4) → (5) → (6) → (7) → (6) → (5) → (4) → (3) → (2) → (1) in Fig. 7. It should be noted, however, that the situation (1) and (7) are undesirable position. If the tool moves to the position (1) or (7), the edges of the partition tend to be over-polished. In order to overcome this problem, we consider a parameter \( h \) (max. height) which is the length from the lowest position to the highest one. The controller used in the robot controls the tool position so as not to overrun (2) and (6). The steps of the CL data, which have a higher value than \( h \), are skipped. If the skipped step has the value for a pick feed, e.g. 0.2 [mm], then the position feedforward controller shown in Fig. 8 extracts the value and give it to the servo controller. Consequently, the common CL data can be directly applied if \( h \) is given according to the tool's shape and the size of workpiece.

3.4 Position Feedback Control of Mounted Abrasive Tools

Figure 8 shows the block diagram of the proposed hybrid position/force controller installed in the mold polishing robot, which is used at the first polishing process. When a workpiece with curved surface is polished, force and position controls should be simultaneously performed in suitable directions. In the normal direction, the force feedback control law which is called the impedance model following force control, yields a velocity vector \( v_r(k) \). In the tangent direction, the position feedforward control law based on CL data generates another velocity command \( v_p(k) \). \( v_r(k) \) is given through an open-loop action in order not to interfere with \( v_p(k) \). Note that using only \( v_p(k) \) is not enough to achieve constant pick feed control along the CL data. Hence, a position feedback loop with a loose gain is added in Fig. 8 so that the abrasive tool will not stray from the desired trajectory. The position feedback control law generates a velocity \( v_p(k) \) as follows:

\[
v_p(k) = K_s \left[ x_r(k) - x(k) \right]
\]

where \( K_s = \text{diag}[K_{xv}, K_{xw}, 0] \) and \( x_r(k) \) is the velocity transformation gain matrix and desired position vector included in \( r(k) \), respectively. Note that \( K_{xv} \) and \( K_{xw} \) should be set as small values in order not to disturb the force control system. Finally, the velocities \( v_r(k), v_p(k) \) and \( v_p(k) \) are summed up, and those of which are given to the reference of the Cartesian-based servo controller.

3.5 Learning of Desired Trajectory

\( P'(k) \) in Fig. 8 is composed of the measured position vector \( x'(k) \) and direction vector \( o'(k) \). \( x'(k) \) is the position at the tip of the tool calculated from the inverse kinematics. \( o'(k) \) is the direction vector to which \( v_p(k) \) is given. \( P'(k) \) is recorded into the memory area of the PC and referred as the desired trajectory for the next process. Note that the CL data are used only for the initial desired trajectory and also the approximated accuracy of the CL data referred by the polishing robot is considerably rough compared to one used in the NC machine tools. However the hybrid position/force control method illustrated in Fig. 8 can absorb the errors and uncertainties of the shape and positioning.

4 Polishing Experiments of PET Bottle Molds with Curved Surface

4.1 Experimental Setup

In this section, to prove the validity and effectiveness of the proposed mold polishing robot, experiments on polishing before finishing were conducted using an aluminium workpiece machined by an NC
machine tool, where the main task is to remove all cusp marks. The cusp height is about 0.3 mm. The CAD model for a test workpiece is shown in Fig. 5. The polishing before finishing is one of the most important processes to make the best beauty of mirror finishing. If the undesirable cusp marks are not uniformly removed in advance, it is so difficult to finish the workpiece with mirror surface without spending much time for the finishing process. The polishing robot consists of an industrial robot MOTOMAN UP-6, PC for real-time control, force sensor, mounted abrasive tool, and a vice. Figure 9 shows the overview of the polishing robot used in the experiment.

4.2 Polishing Condition

A workpiece of aluminum was fixed along the y-axis in robot base coordinate system with a vise as shown in Fig. 10. The initial CL data were generated with a zigzag path along the cross section of the workpiece as shown in Fig. 5. Mounted abrasive tools are usually attached to electric-driven tools, whose torques give the polishing power to the abrasive tools. When the electric-driven tools are manually used by skilled workers, the contact force is given at the neighborhood of 500 [gf]. On the other hand, when the skilled workers polish by friction forces using a simple bamboo stick with a sand paper through a rubber, the contact force is given about from 1 to 4 [kgf]. In this experiment, since the rotation of the mounted abrasive tool is locked and the polishing task is conducted with the kinetic friction force composed of Coulomb and viscous frictions, the desired polishing force is set as 3 [kgf]. Because of locking the rotation of the tool, undesirable complex vibrational noises, which are the most serious problem in putting the force sensor between the tip of the robot arm and the tool, are scarcely observed. The force sensor measurements are filtered through a cut off frequency 500 [Hz]. The surface is polished through three processes making the grain size of the abrasive tool smaller gradually, i.e., from #220, #320 to #400. Figure 11 shows the mounted abrasive tools with a shank 6 [mm] used in the experiment. To obtain a surface with a higher quality, another zigzag path in the longitudinal direction as shown in Fig. 12 is also used for the basic trajectory of the abrasive tool. These two paths shown in Fig. 5 and Fig. 12 are alternately used. In order to uniformly use the contour of the ball-end type tools, the tools are slowly rotated at from 1 to 50 [deg/s] using the 6-th axis of the industrial robot. Other polishing conditions are tabulated in Table 1. The parameters $M_1$, $B_1$, $K_1$, and $h$ are tuned in advance.
Table 1: Polishing conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base path along the curved surface</td>
<td>Zigzag</td>
</tr>
<tr>
<td>Pick feed in longitudinal direction</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Radius of abrasive tool R</td>
<td>5 mm</td>
</tr>
<tr>
<td>Grain size of abrasive rubber tool</td>
<td>#220, #320, #400</td>
</tr>
<tr>
<td>Rotational velocity of 6-axis</td>
<td>50 or -50 deg/s</td>
</tr>
<tr>
<td>Rotational limits of 6-axis</td>
<td>-90 &lt; θ &lt; +90 deg</td>
</tr>
<tr>
<td>Max. height h</td>
<td>14 mm</td>
</tr>
<tr>
<td>Desired polishing force $F_p$</td>
<td>3 kgf</td>
</tr>
<tr>
<td>Tangent directional velocity $v_t$</td>
<td>6 mm/s</td>
</tr>
<tr>
<td>Desired mass coefficient $M_{x_c}, M_{y_c}, M_{z_c}$</td>
<td>0.01 kgf - s²/mm</td>
</tr>
<tr>
<td>Desired damping coefficient $B_{x_c}, B_{y_c}, B_{z_c}$</td>
<td>30 kgf - s/mm</td>
</tr>
<tr>
<td>Force feedback gain $K_{x_c}, K_{y_c}, K_{z_c}$</td>
<td>1.0, 1.0, 0.3</td>
</tr>
<tr>
<td>Position feedback gain $K_{x_p}, K_{y_p}$</td>
<td>0.005, 0.005</td>
</tr>
<tr>
<td>Sampling width $\Delta t$</td>
<td>10 ms</td>
</tr>
</tbody>
</table>

through a simple experiment of surface following control.

4.3 Case of a Cylinder Type Workpiece

As the first case study, a cylinder type shape as shown in Fig. 13 is examined. The mounted abrasive tool approaches to the initial contact point with 1 [mm/s], then the CL data are projected into the tangential directions of the constraint surface. It was observed from the experimental result that undesirable force errors occurred when the tool went down from the top position, i.e., (2) → (3) or (6) → (5) as shown in Fig. 7. This is due to the fact the polishing force was controlled in a high stiff dynamics system; the polishing system is based on an industrial robot; and there exist almost zero damping factors in the jig, workpiece, attachment, abrasive tool and force sensor. The surface state after polishing was evaluated by both eye checking and touch feeling with index and middle fingers; a beautiful surface finishing without over-polishing around the edge was observed. When the proposed polishing robot is used, the polishing force can be uniformly generated on the average compared to skilled workers. This would be a reason why such an effectiveness of polishing was obtained drastically. An example of the control results is shown in Fig. 14, which is the time histories of force sensor measurements in $x$-, $y$- and $z$-directions for 120 seconds after starting the polishing.

4.4 Case of a PET Bottle Mold

As the second case study, we applied the polishing robot to a PET bottle mold with a complex curved surface as shown in Fig. 10. Figure 15 shows the polishing scene using an other abrasive tool. As can be seen, the workpiece has continuous surfaces except for the edges, i.e., parting lines. Figure 16 shows the control result of the polishing force in case of using the CL data shown in Fig. 5. When an abrasive tool return the parting line, the contact force tends to be unstable. Therefore, conventional polishing robots are not suitable for polishing these types of models.
4.5 Case of Using the Learned Trajectory

In this section, a technique to acquire a more precise desired trajectory is proposed. The CL data are used only for the initial polishing process. In polishing, the actual trajectory of the robot is stored as shown in Fig. 8. The actual trajectory is used for the next polishing process as shown in Fig. 17. For example, if a workpiece is polished through 4 processes, i.e. using 4 kinds of abrasive tools, then superscription i increases as 1, 2, 3 and 4. As described in section 3.5, CL data is used for the initial desired trajectory when i = 1. In other words, the desired trajectory is modified such that the summation of force error $\Sigma_{j=1}^{n} |F(k) - F_j|$ ($n$ : total task time) approaches to zero, every after the polishing robot finishes the polishing of the workpiece. Figures 18 and 19 show some of the x- and z- directional acquired trajectories, respectively. In this case, the tip of the tool moved as (4) → (5) → (6) → (5) → (4) → (3) → (2) in Fig. 7. Figure 20 shows the control result of the polishing force in case that the acquired trajectory as shown in Figs. 18 and 19 was used. It is observed from the result that the force control performance can be improved by using the acquired trajectory. Furthermore, the mirror finishing as shown in Fig. 21 was confirmed after wiping the surface using a cloth containing a polishing compound CR2O3.

It has been generally considered to be impossible and nonsense in manufacturing industries of metallic molds that the molds are polished and finished by using industrial robots whose repetitive position accuracy are 0.1 [mm] at most. However, the experimental results described in this section proved that our proposed high performance polishing robot, in which the learning-based hybrid position/force controller was installed, could overcome this problem.

5 Conclusions

Although the design and machining processes in manufacturing industries of metallic molds have been remarkably automated by 3D CAD/CAM systems and NC
machine tools, the polishing which is the most important and last process is still supported by skilled workers.

In this paper, a high precision polishing robot with a learning-based hybrid position/force controller has been proposed for PET bottle molds with curved surface. The polishing robot was developed based on an industrial robot with a Cartesian servo controller available for Windows API functions. It was found from preliminary experiments that the loose interference between the position and force controls is so effective to successfully execute skillful polishing tasks. Fundamental polishing experiments of concave aluminium molds were also conducted, and consequently the undesirable cusp marks could be removed sufficiently. Furthermore, a mirror finishing was confirmed after wiping the surface using a cloth containing CR2O3.

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References