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Replication of skilled polishing technique with serial–parallel mechanism polishing machine

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ABSTRACT

Currently, viscoelastic polymers are used to coat automotive body to prevent scratches. On the other hand, the application of a polymer with high viscoelasticity makes the repair polishing process of the coated body more difficult. Hence, performing the polishing process requires the operator to be technically skilled. However, the number of workers with necessary technical skill has been decreasing because of an aging population. In addition, the surface quality and process time are dependent on the proficiency level of the worker. To automate the repair polishing process, in our past research, a serial–parallel mechanism polishing machine was developed to simultaneously control the tool trajectory, tool posture, and polishing force. The present study aims to construct a replication system of a skilled polishing technique on the basis of the above three physical parameters by applying the developed polishing machine. First, the tool trajectory, tool posture, and polishing force of a skilled worker, which reflect the polishing technique, were acquired using a high-speed camera and a dynamometer. By inputting the acquired data to the developed machine, the machine can copy the polishing technique because the tool trajectory, tool posture, and polishing force can be independently controlled. From the results of the polishing test, the surface quality after polishing was comparable to that of the skilled worker output, which satisfies the criteria of surface quality.

1. Introduction

Automotive body is currently coated by viscoelastic polymers [1] to prevent scratches. During the coating process, dust or contamination can get mixed with the coating and lead to an undesirable appearance. Therefore, the coated body needs to be polished for finishing. The repair polishing process is done manually by skilled workers because the application of viscoelastic polymers makes the polishing process more difficult [2]. However, the number of workers with the necessary technical skill has been decreasing because of an aging population [3]. In addition, the skilled polishing technique has not been handed down from elderly skilled workers to younger people. As a result, the surface quality and process time differ depending on the proficiency level of the worker. Therefore, skill-independent automation technology for repair polishing [4–7] is required in the automotive industry.

In our past research, a serial–parallel mechanism polishing machine [8] was developed to simultaneously control the tool trajectory, tool posture, and polishing force. The developed polishing machine consisted of the serial (XY stage) and parallel mechanism components. The XY stage can control the tool trajectory, and the parallel mechanism can independently control the tool posture and polishing force in the z-axis direction by applying the mode-decoupling method based on a quarry matrix [9,10]. In particular, the polishing force is controlled by applying both disturbance observer (DOB) [11,12] and polishing force observer (PFOB) [8]. By implementing the PFOB, force control is realized without external sensors, which leads to a reduction in mechanical stiffness and an increase in production cost and frequent maintenance. From the abovementioned method, the tool trajectory, tool posture, and polishing force of the developed polishing machine are independently and simultaneously controlled.

The skilled worker would mainly control the tool trajectory, tool posture and polishing force according to the condition of the workpiece in the manual polishing operation. As a result, the surface quality after polishing could be improved. To automate the skilled polishing process by the developed machine, the tool trajectory, tool posture and polishing force data of the skilled worker according to the condition of the workpiece are required. Although a polishing skill replication by a closed loop control is eventually needed according to the condition of the workpiece, the replication by an open loop control like a copying polishing would be

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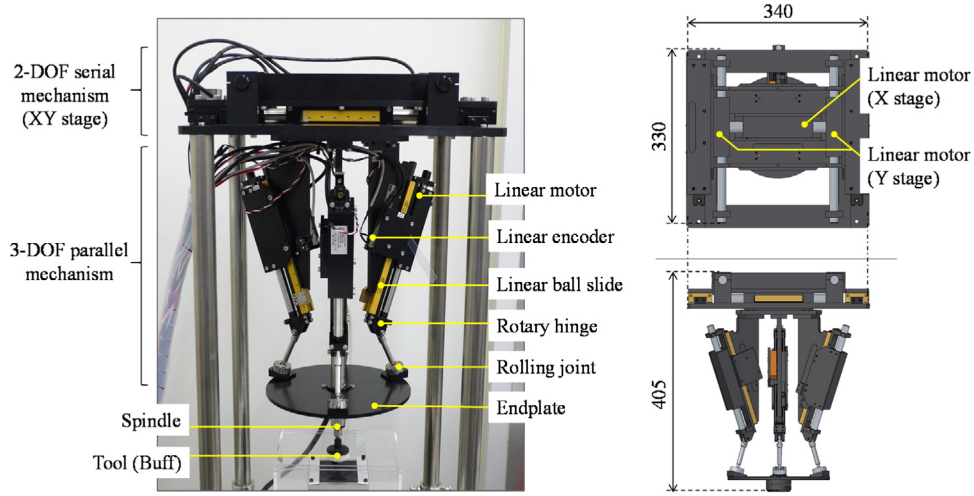

Fig. 1. Schematic of the serial–parallel mechanism polishing machine.

applicable for single workpiece. Hence, the purpose of the present study is to construct an acquisition and a replication system of the skilled polishing technique by applying the developed polishing machine and the developed control system, which is based on the concept of the open loop control. The workpiece used in both acquisition and replication system is the viscoelastic polymer coated on the flat surface. During the manual polishing operation, the tool trajectory, tool posture, and polishing force, which reflect the polishing technique, were acquired from the skilled worker using a high-speed camera and a dynamometer. The acquired data were input into the developed machine, and the machine could copy the polishing technique because the tool trajectory, tool posture and polishing force are independently controllable. Through the polishing tests to the viscoelastic polymer coated on the flat surface, the validity of the constructed replication system was evaluated.

2. Serial–parallel mechanism polishing machine

Fig. 1 shows the schematic of the serial–parallel mechanism polishing machine [8]. This machine consists of a three-degree-of-freedom (DOF) parallel mechanism component and a two-DOF serial mechanism component (XY stage). The three-DOF parallel mechanism is assembled below the XY stage. The XY stage has three active actuators (one in the X stage and two in the Y stage), and the three-DOF parallel mechanism has three active actuators set at 120° intervals. All the active actuators are coreless linear motors, which can be smoothly moved. At the lower end of the shaft in the parallel mechanism, the rod is connected to the rotary hinge of a one-DOF linkage. The other end of the rod is attached to the endplate through a rolling joint. This structure allows the parallel mechanism to move along the z direction, the x-axis rotation (pitching), and the y-axis rotation (yawing). Each axis has one optical linear encoder. The tool spindle is attached to the endplate of the parallel mechanism. The tool employed is a wool buff. The z-axis polishing force and the tool posture (pitching and yawing) are controlled at the three-DOF parallel mechanism, and the tool trajectory in the XY plane is controlled at the XY stage. The specifications of the serial–parallel mechanism polishing machine are listed in Table 1.

Table 1
Specifications of the serial–parallel mechanism polishing machine.

Size of machine (X × Y × Z)	330 mm × 340 mm × 405 mm
Weight of machine	8.10 kg
Movement range (X × Y × Z)	75.4 mm × 50.4 mm × 44.4 mm
Angle range (yawing, pitching)	15.90°, 18.18°
Size of buff tool	16-mm radius
Resolution of linear encoder	1.0 μm
Rated thrust force (X stage, Y stage)	15 N, 28 N
Rated thrust force (each link of the parallel mechanism)	8.9 N
Control sampling time	250 μs
Cutoff frequency of the position control	200 rad/s
Cutoff frequency of the force control	200 rad/s

3. Methodology of controlling the serial–parallel mechanism machine

3.1. Position control based on DOB

In the automation of the repair polishing, the accuracy of the position and force control is an important factor. The DOB [11,12] is an effective method of canceling a disturbance force, which is defined as the sum of polishing load F_{polish}, friction force in the guide ways F_{fric}, fluctuating forces caused by variations in the motor thrust force coefficient ΔK_t, and mass variation ΔM. The disturbance force is estimated using the current reference I_a^{ref}, which is applied to the actuator, and velocity response v^{res}. Velocity response v^{res} is calculated by the numerical differential of position response x^{res} read by a linear encoder. From the above description, the disturbance force is expressed as follows:

$$F_{\mathrm{dis}} = F_{\mathrm{polish}} + F_{\mathrm{fric}} + \Delta K_t I_a^{\mathrm{ref}} - \Delta M s v^{\mathrm{res}} = K_{tn} I_a^{\mathrm{ref}} - M_n s v^{\mathrm{res}} \tag{1}$$

where subscript “n” is a nominal value. In practice, a first-order low pass filter (LPF) is inserted to suppress the noise generated from the velocity differential. Therefore, the estimated disturbance force is expressed as follows:

$$\hat{F}_{\mathrm{dis}} = \frac{g_{\mathrm{dis}}}{s + g_{\mathrm{dis}}} \left(K_{tn} I_a^{\mathrm{ref}} - M_n s v^{\mathrm{res}} \right) \tag{2}$$

where $\hat{}$ means an estimated value and g_{dis} is the cutoff frequency of the LPF. Using the feedback of the compensation current equivalent to the estimated disturbance force, the disturbance up to the cutoff frequency can be cancelled. The position control system using the DOB is designed (Fig. 2). Because the disturbance cancellation serves as an integrator, a proportional–derivative controller is suitable to enhance the positioning performance. The position controller is designed using the following equation:

$$I_a^{\mathrm{ref}} = \frac{M_n}{K_{tn}} \left\{ K_{pp} \left(x^{\mathrm{cmd}} - x^{\mathrm{res}} \right) + K_{vp} \left(v^{\mathrm{cmd}} - v^{\mathrm{res}} \right) + a^{\mathrm{cmd}} \right\} \tag{3}$$