Precision Engineering xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Simultaneous tool posture and polishing force control of unknown curved surface using serial-parallel mechanism polishing machine

Yuta Oba*, Yasuhiro Kakinuma

Department of System Design Engineering, Keio University, Japan

ARTICLE INFO

Article history:
Received 10 January 2017
Accepted 16 January 2017
Available online xxx

Keywords:
Polishing
Parallel mechanism
Unknown curved surface
Automation
Sensor-less force control
Skilled technique

ABSTRACT

In automotive manufacturing, the repair polishing process of an automotive body is still manually performed by skilled polishing workers. This is because skilled workers can appropriately control the polishing motion and force according to the workpiece conditions based on their experience. However, the number of skilled workers has been decreasing. Additionally, the skill development of younger workers has not been satisfactorily conducted. To overcome such problems, in a previous research investigation, we developed a serial-parallel mechanism polishing machine that effectively reproduced the polishing motion and force of skilled workers. This replication system, however, had limited use because the acquired polishing techniques could not adapt to various workpiece conditions, such as shape and size. The present study aimed to expand the polishing method for application to curved surfaces, in other words, adapt the replication system to changes in the workpiece shape. In the past polishing methods for curved surfaces, the workpiece shape was acquired by using CAD data or external sensors that often led to an increase in process time and cost. However, the newly proposed method in this study requires neither CAD data nor external sensors, and was able to effectively achieve simultaneous posture and force control on unknown curved surface. The experimental results showed that the skilled polishing techniques were successfully replicated on an unknown curved surface and the surface roughness was greatly improved by integrating the newly proposed method into the skilled polishing replication system.

1. Introduction

The repair polishing process for an automotive body is important for satisfying the high surface quality requirements of automotive manufacturing. The polishing process is still manually carried out by workers with the required polishing technique. This is because the skilled worker is capable of adjusting the polishing motion and force according to the workpiece conditions based on their experience. However, the number of skilled workers has been decreasing because of an aging population, and the skill development of younger workers has not been satisfactorily conducted [1]. Therefore, polishing automation technology has been proposed in many research studies so that ultimately it can replace manual polishing and improve polishing efficiency [2–8].

In our previous research, a replication system of the skilled polishing technique was developed using a serial-parallel mechanism polishing machine [7]. This polishing machine was capable of independently controlling the polishing motion and force, namely, the displacement on x-y plane (horizontal plane), angular displacements in yawing and pitching modes, and force in z-axis mode [8]. Therefore, the skilled polishing techniques of these three physical parameters were acquired from skilled workers to replicate the skilled polishing process using the polishing machine. By inputting the acquired data into the developed polishing machine as command values, the skilled polishing process could be successfully replicated. However, the constructed replication system was considered to be incomplete because the skilled polishing techniques did not change according to the workpiece conditions such as shape and size. Therefore, a method for detecting changes in workpiece conditions was required to use the proposed skilled polishing replication system for polishing automation.

This study focuses on only the workpiece shape. The previously proposed system of skilled polishing replication could be used only on flat surfaces. However, actual automotive bodies are not flat, but curved. In general, both the tool posture and the direction of the polishing force should be controlled normal to the curved surface. Therefore, an automated polishing method is required to adapt the skilled polishing replication system to the curved surface. In past research investigations, the polishing automation for curved

* Corresponding author at: Department of System Design Engineering, Keio University, 3-14-1 Hiyoshi, Kohoku, Yokohama, Kanagawa 223-8522, Japan.
E-mail address: ohba@ams.sd.keio.ac.jp (Y. Oba).

http://dx.doi.org/10.1016/j.precisioneng.2017.01.006
0141-6359/

Nomenclature

F_{dis}	Disturbance force [N]
F_{reac}	Reaction force [N]
F_{fric}	Friction force [N]
K_t	Motor thrust force coefficient [N m/A]
I_a	Motor current [A]
M	Mass [kg]
x	Position [m]
v	Velocity [m/s]
a	Acceleration [m/s^2]
θ	Angle [rad]
$(Subscript)_n$	Nominal value
$(Superscript)^{cmd}$	Command value
$(Superscript)^{ref}$	Reference value
$(Superscript)^{res}$	Response value
$Caret$	Estimated value

surfaces was achieved using CAD data [9–11] or external sensors [12–14]. For example, Z. Jianming et al. [11] proposed a polishing method for aspheric surfaces by acquiring the workpiece shape from CAD data prior to the polishing operation. However, the workpiece shape from the CAD data does not always correspond to the real shape because the workpiece shape from the CAD data does not account for installation error. Therefore, the polishing process using CAD data requires an additional step for position adjustment depending on human skill, and thus the entire process duration increases. S. Kamezaki et al. [12] proposed a polishing method for metal molds with force sensors. In their work, the workpiece shape was estimated based on reaction force information by a 6-axis force sensor installed in the polishing tool. Z. Yang et al. [14] used a touch trigger probe for surface measurement to achieve edge polishing. However, applying external sensors generally results in increased production costs and frequent maintenance. To eliminate the abovementioned problems, the simultaneous control method of tool posture and polishing force in the normal direction of curved surfaces, which is independent of CAD data and external sensors, is proposed in this study.

The purpose of the present study is to adapt the skilled polishing replication system to curved surfaces with the proposed control method. First, a tool posture control method of an unknown curved surface was proposed. The posture angles in yawing and pitching modes were determined based on force information acquired from the parallel mechanism component with a reaction force observer [15–17]. Second, a normal force control method based on tool posture information was proposed. Using these proposed methods simultaneously, the tool posture and polishing force were controlled in the normal direction of unknown curved surfaces. From the experimental results, the skilled polishing techniques were successfully replicated on the unknown curved surface with the newly proposed method. In addition, the surface quality after polishing fully satisfied the surface quality criteria.

2. Serial-parallel mechanism polishing machine

2.1. Composition of mechanism

Fig. 1 shows an overview of the serial-parallel mechanism polishing machine [8]. The parallel mechanism is suitable for polishing automation because it enables high precision and high-speed movements compared to the serial mechanism. However, the parallel mechanism machine is often not used in industrial polishing automation owing to its limited workspace. To address this drawback, a two-degree-of-freedom (DOF) serial mechanism (XY stage) that provides a larger workspace is assembled in between the base frame and the three DOF parallel mechanism. The XY stage has three linear motors (one in the X stage and two in the Y stage) and the parallel mechanism has three linear motors positioned at 120° intervals. At the lower end of the shaft in the parallel mechanism, the rod is connected to the revolute joint of one-DOF linkage. The other end of the rod is attached to the endplate through a spherical joint. This structure allows the parallel mechanism to move in the z-direction, as well as x-axis rotation (pitching) and y-axis rotation (yawing). Each axis has one optical linear encoder. A wool buff is attached to the lower end of the spindle. The polishing force and the tool posture are independently controlled at the 3-DOF parallel mechanism, and the displacement of the tool on x-y plane is controlled at the XY stage. The specifications of the developed polishing machine are listed in Table 1.

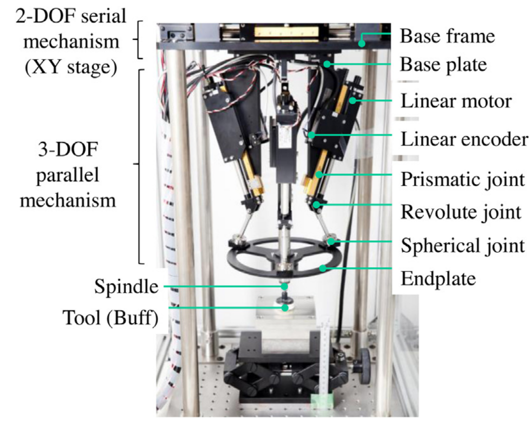

Fig. 1. Serial-parallel mechanism polishing machine.

Table 1
Specifications of 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
Control sampling time	250 μs

2.2. Position and force control theory

The motion of the developed machine is controlled based on disturbance observer (DOB) [18] and [19]. DOB is designed to cancel disturbance forces. The estimated disturbance force is obtained from the velocity response v^{res} and the current reference I_a^{ref} as shown in Eq. (1).

$$F_{dis} = F_{reac} + F_{fric} + Mg + \Delta K_t I_a^{ref} - \Delta M s v^{res} = K_{tn} I_a^{ref} - M_n s v^{res} \quad (1)$$

The velocity response v^{res} is calculated by the differential of the position response x^{res} read by the linear encoder, and the current reference I_a^{ref} is applied to the actuator. Fig. 2 shows a block diagram of the position control based on DOB. A first order low pass filter (LPF) is inserted in order to suppress the noise generated from the differential of the velocity. Also, the estimated disturbance is fed back as a current value to actively cancel a bad influence of the disturbance to the control system. A proportional-derivative (PD) controller is suitable because the disturbance cancellation serves as an integrator. The positioning performance and robustness are determined by the position controller and DOB, respectively.

Please cite this article in press as: Oba Y, Kakinuma Y. Simultaneous tool posture and polishing force control of unknown curved surface using serial-parallel mechanism polishing machine. Precis Eng (2017), http://dx.doi.org/10.1016/j.precisioneng.2017.01.006