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Design of manipulator for gantry-type finishing machine

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Abstract
This paper presents a novel design of a manipulator for surface finishing of large work space. Gantry type finishing machine with machining manipulator is proposed for achieving CNC-based automated surface finishing system. The machine is composed of gantry, slide table and 4-axis manipulator. Two translational axes locate the end-effect at the specified position, then four revolutionary motors carry out finishing works adapting a curved surface. This structure provides the advantage of both robot manipulator and gantry type machine in terms of large workspace and high stiffness. The motion of the manipulator is performed by the parallelogram mechanism and angular motions. Also, motion control system with inverse dynamics feedforward model is employed to stand against the abrupt change of cutting force in the multibody dynamic simulation. It is expected that the designed manipulator can be adopted in the finishing works, which has been suffered from weak stiffness of the conventional industrial robot.

Keywords : machining manipulator, parallelogram, surface finishing

1. Introduction

A finishing process to achieve high quality surface has been treated as a most costly time-consuming task in the manufacturing process. As the demand for large-sized molds and 3D printing products increases, the automated finishing process becomes more important. Conventional CNC machines are already able to achieve desired quality and productivity in the automated finishing processes. However, this approach has essential limitations because it can be hardly applied for a complicated geometry and large scaled workpiece [1].

A robotic manipulator offers a cost-effective and flexible machining alternative for automated finishing process. However, it has a critical disadvantage of the significantly low stiffness that results in considerable path deviation, particularly under machining force [2]. To solve this problem, it is necessary to increase the stiffness of the manipulator and to control with the consideration of abrupt change of the machining force that occurs during machining operation.

2. Description of finishing machine

A finishing machine is composed of gantry, slide table and angular manipulators. 4-DOF manipulator mounts a rotating tool at the end-effector and carries out the surface finishing operation. Since the manipulator have different stiffness value depending on the posture and position of the end-effector, the machining is performed only in a limited area producing an allowable stiffness at the specified position.

By attaching the manipulator to the gantry, the manipulator can be located on the desired work area in terms of position and orientation. In our study, a slide table moves along the planar motion. In machining process, the manipulator works at the limited space by combining swing and angular motions, while the dead weights of manipulators including tool holder and motors can stand against a part of cutting resistance by adopting a specialized control technique.

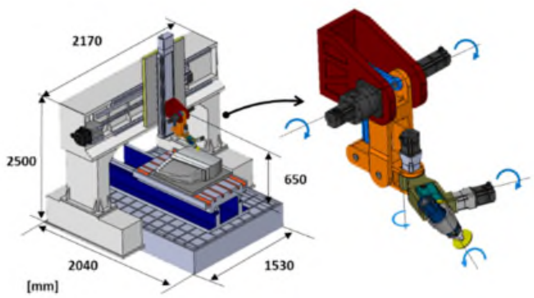

Figure 1 Conceptual design of robo-finishing machine

Through this control regime, manipulator can stand the frequently abrupt changes of cutting force as well as total cutting force with enough stiffness.

Another feature is to adopt a parallelogram mechanism which has an advantage of its kinematic design. The weight of second motor is not loaded to the first motor, because it is attached to the base structure at the other side of the first motor. A closed chain is generated where the first two joint connect $l_1$and l_a to base, respectively. Where $l_a = l_c$ and $l_b = l_1$ in view of the parallelogram structure. Two motors fixed at the base drive the two input links (l_1 andl_a) and provide two dimensional motion at the tip(A) of the arm. The details of the parallelogram mechanism is not described due to the editorial limitation. Although this mechanism requires more links and passive joints, it can move the center of mass to backward, and decrease the total system load. Table 1 and 2 indicate the dimensions and weights of the manipulators to be used in the simulation.

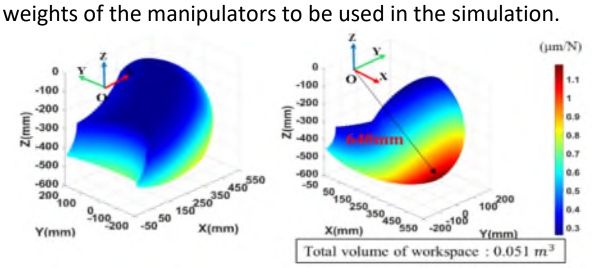

Figure 2 Maximum compliance for an arbitrary force in workspace

The figure 2 shows the workspace determined by the inverse kinematics and joint limits. It also represents maximum compliance for an arbitrary force in Cartesian workspace. Total volume of workspace is 0.051m^3 and maximum reach is 640mm.

Table 1 Dimension of links

	l_1	l_2	l_3	l_4	l_a	l_b	l_t
Length[mm]	350	100	220	50	150	350	50
Mass[kg]	6.2	4	2.5	1.4	0.5	0.3	1.2

Table 2 Mass of motors

	$motor1$	$motor2$	$motor3$	$motor4$	$motor5$
Mass[kg]	3.1	2.3	1.7	1.7	1.4

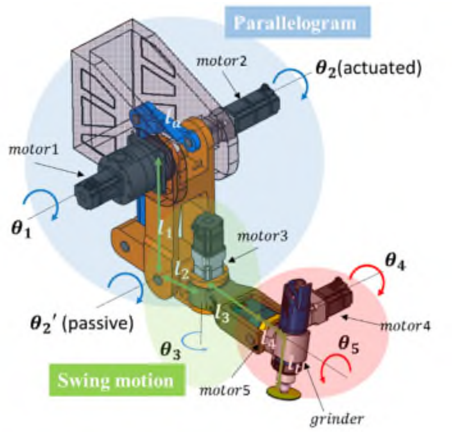

Figure 3 Conceptual design of manipulator

3. Error analysis

This section describes a cutting force-induced machining error when machining a hemispherical shape of mold workpiece having 200mm diameter.

3.1. Force-induced errors

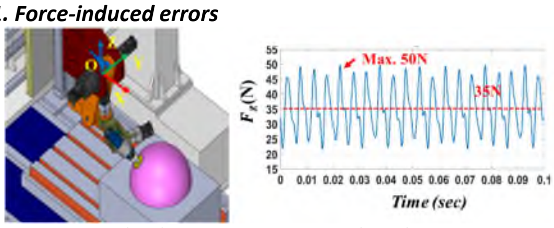

Figure 4 3D view (left) and machining force (right) in simulation

Table 3 Joint stiffness values

Joint stiffness [KN·m/rad]	θ_1	θ_2	θ_3	θ_4	θ_5
	410	936	400	360	360

The machining accuracy is determined by the loop stiffness at the end-effector. In this research, most of the compliance is composed of the torsional stiffness at the revolutionary joint. The machining error is simulated by assuming the torsional stiffness as the linear spring indicated in table 3. [1]

3.2. Simulation result

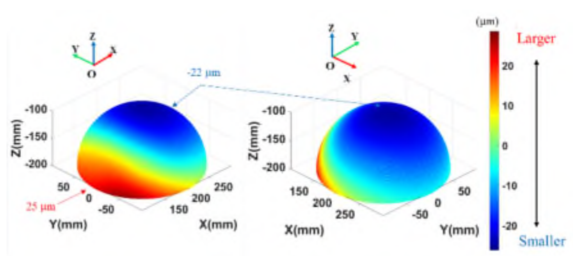

Figure 5 Magnitude of total error when machining hemisphere (Normal force: 50N)

The simulation results show that the maximum error reaches 25 μm level when hemispherical shape was machined with designed manipulator. Path deviations due to quasi-static errors becomes more than those caused by force-induced errors.

4. Control simulation

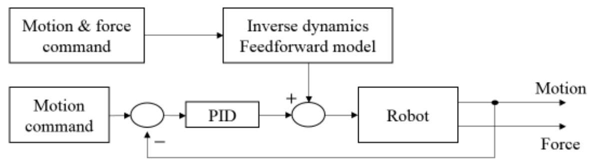

Figure 6 Servo control process (top), and PID-based feedforward control (bottom)

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + N(\theta,\dot{\theta}) = \tau + J^T(\theta)(f_n + f_t) \quad (1)$$

The dynamic performance of manipulator can be estimated by adopting a virtual servo drive and controller in multibody dynamic simulation. Also, an inverse dynamics feedforward control is adopted as an indirect force control method to stand against the frequently abrupt change of machining force.

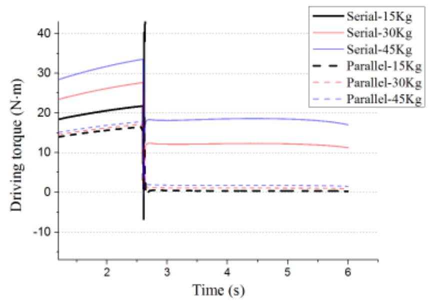

Figure 7 Simulation result of abrupt change when entering workpiece (driving torque of motor 2)

The figure 7 compares serial and parallelogram manipulator applying the abrupt change condition of cutting force when entering workpiece. The driving torque of the parallel mechanism becomes nearly zero, and it indicates that the cutting resistance can be compensated by this specific design.

5. Conclusion

This paper describes manipulator design for surface finishing works in the gantry-type machine. Manipulator has a parallelogram mechanism to enhance dynamic performance, and revolutionary joints. The simulated machining error show that the total error reaches up to 25µm when hemispherical shape was machined with designed manipulator. Control simulation using a PID-based inverse dynamics feedforward control shows that the parallelogram mechanism improves significantly the dynamic performance.

Acknowledgement

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