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Research on Velocity Servo-Based Hybrid Position/Force Control Scheme for a Grinding Robot

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Abstract. In this paper, a velocity servo-based hybrid position/force control scheme for a grinding robot is presented. It simultaneously performs stable force control and exact position control along curved surface for a grinding robot. The force feedback loop changing the force to velocity, which will be used in the velocity servo-based robot, can control the force directly and has a faster response. The position feedback loop controls the grinding tool in a desired trajectory in Cartesian space. An overview of the control algorithm as well as the force data signal processing and the communication between force sensor and robot controller is described.

Introduction

In most cases, position control is appropriate when the industrial robot application is not requiring a compliant system to solve, but when any contact is made between the industrial robot end-effector and the environment, such as grinding, polishing, deburring, assembly and so on, position control might not suffice. It is necessary to control not only the position of the robot but also the contact force between the end-effector and the environment. So, force control of an industrial robot is indispensable for a grinding robot system.

A number of schemes have been proposed for robot force control [1, 2], and grinding robot systems with force control have already been studied and developed [3, 4, 5]. However, many of industrial robot use position control scheme, which is based on position servo motor, has a poor response compared with velocity servo motor. The scheme based on position control for robot grinding application can only achieve a tradeoff between position and force. In this paper, a velocity servo-based hybrid position/force control scheme for a grinding robot is presented. This control scheme is based on velocity servo motors that have faster response compared with position servo motors. It simultaneously performs stable force control and exact position control along curved surface for a grinding robot. The control scheme incorporates a method for removing the gravity influence of the grinding tool caused by motion. The communication between the force sensor and the robot controller will be discussed.

The paper is organized as follows: Firstly, the control scheme for a grinding robot is presented. Secondly, the communication between the force sensor and the robot controller is described. Thirdly, we will discuss the force signal processing. Finally, we will give a simulation for the control scheme.

Control Scheme of the Grinding Robot

Fig. 1 shows the block diagram of the grinding robot control system. In the mass, there are two main parts of the control scheme. One is velocity servo-based control algorithm. We set up the relationship between the velocity and the force, and it can control the force directly. The other is hybrid position/force control algorithm. The position and force can be separately controlled by selection matrix S. S=$diag(s_j)$ (j=1,2,...,n), n is the number of degree of freedom, when s_j=1, the jth DOF must be force controlled, otherwise it must be position controlled.

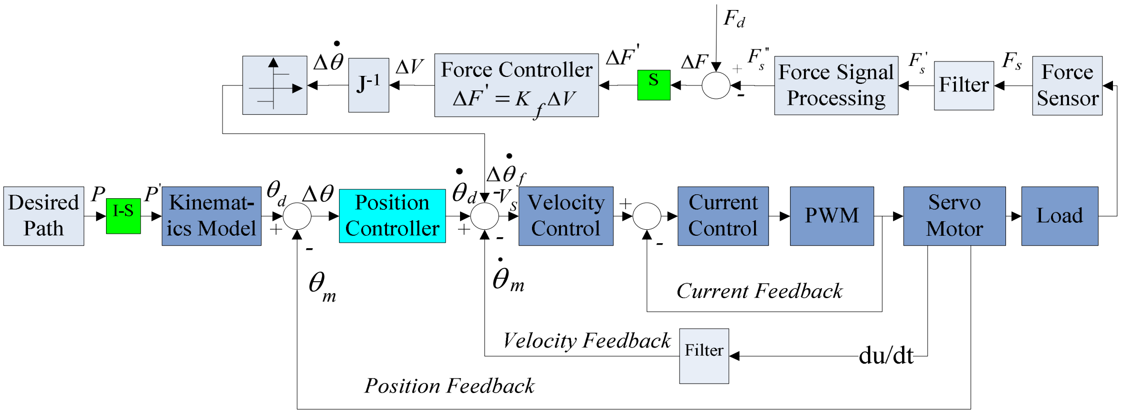

Fig. 1 Block diagram of the grinding robot control system

As shown in Fig. 1, there are two main loops in the block diagram. One is the force control loop, the other is position control loop. In force control loop, the force sensor measures the contact force F_s. We get F_s' from a filter, which can remove the frequency interference. Force signal processing model includes the grinding tool gravity compensation and the force data transformation from the force sensor frame to the grinding tool frame. Its output is F_s''. The desired force is F_d. The force error $\Delta F = F_d - F_s''$. S is the selection matrix. In this paper, the desired force is controlled to be zero except the Z axis that is controlled to move the grinding tool towards the workpiece. So $S = diag(0,0,1,0,0,0)$, $\Delta F' = S(F_d - F_s'')$. The relationship between velocity and force is $\Delta F' = K_f \Delta V$, where ΔV is the grinding tool velocity error due to the contact force error, $\Delta V = \begin{bmatrix} \Delta v_x & \Delta v_y & \Delta v_z & \Delta w_\alpha & \Delta w_\beta & \Delta w_\gamma \end{bmatrix}^T$; K_f is the force control coefficient matrix, $K_f = diag(k_x, k_y, k_z, k_\alpha, k_\beta, k_\gamma)$. $\Delta\dot{\theta}$ is the joint velocity error, we get it from $\Delta\dot{\theta} = J^{-1} \bullet \Delta V$, where J is the jacobian of the industrial robot with grinding tool. So far we have discussed the whole force control loop, and the detailed position control loop will be given next.

In position control loop, P is the desired position. X and Y axis are in position control, so $I - S = diag(1,1,0,0,0,0)$. $P' = (I-S) \bullet P$. The kinematics model transforms the tool position to joint position. Its input is P' and output is θ_d, where θ_d is the desired joint position. The joint position error $\Delta\theta = \theta_d - \theta_m$, where θ_m is the joint feedback position. The position controller is a proportion controller. $\dot{\theta}_d = K_p \Delta\theta$, where K_p is proportion coefficient. Velocity servo-based motor's input is V_s, it is described in the following equation:

$$V_s = \dot{\theta}_d + \Delta\dot{\theta}_f + \dot{\theta}_m . \tag{1}$$

Where $\dot{\theta}_d = K_p(\theta_d - \theta_m)$, $\Delta\dot{\theta}_f = J^{-1}\dfrac{1}{K_f}S(F_d - F_s'')$.

Communication between Force Sensor and Robot Controller

In this paper, a six-axis ATI Gamma Force/Torque sensor is used for sensing the contact force. The ATI sensor communicates with the robot controller over Ethernet. It can output data at up to 7000Hz using UDP. This method of fast data collection is called Raw Data Transfer (RDT), RDT provides an easy method to get the forces data. There are six commands in the RDT protocol for different applications. We use 0x0002 command for the grinding robot real-time response application, whose speed is up to 7000Hz.The communication between the ATI sensor and the robot controller is described as Fig. 2:

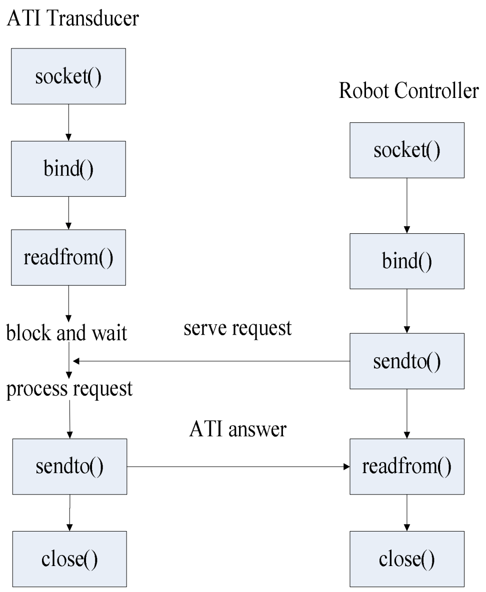

Fig. 2 Communication flow diagram between ATI sensor and robot controller

We use the SOCK_DGRAM to establish the communication between the ATI sensor and the robot controller. Firstly, the ATI sensor and robot controller start up and create socket, respectively. Then we use *bind* command to bind the socket with the network address, which establish port service. The ATI sensor listens for RDT requests on UDP port 49152. If the robot controller wants to communicate with the ATI Sensor, it can use the *sendto* command to send the serve request to ATI Sensor. The ATI Sensor gets the serve request and processes, and then uses the *sendto* command to send the force data to the robot controller. The robot controller uses the *readfrom* command to receive the force data. When the communication is over, we use *close* command to close the socket.

Force/Torque Signal Processing

Fig. 3 shows an end-effector holding a grinding tool. {R}, {S} and {T} are the coordinate frames for the last link of the robot, the force sensor, and the grinder, respectively. In order to get a good grinding effect, the constant force between the grinding tool and the workpiece is needed. The force sensor can only measure the force data in {S} coordinate frame, however, our real interest is in knowing the forces and torques applied at the tip of the tool, {T}. So the transformation that transforms the force/torque vector from {S} to {T} is needed.

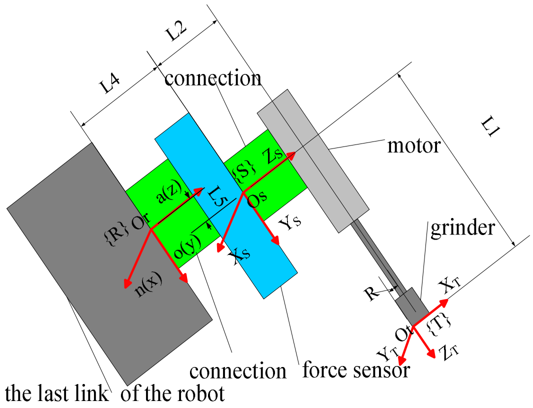

Fig. 3 End-effector of the grinding robot

Or, Os, and Ot are the origins of coordinate for {R}, {S}, and {T}. L4, L5, and L6 are the distances from Or to Os in Z, Y, and X directions. L1, L2, and L3 are the distances from Os to Ot in Z, X, and Y directions. R is the radius of the grinder. So, L5+L1, L6+L3 and L4+L2-R are the distances from {R} to {T} frames in Z, Y, and X directions. Fs and Ft are the forces and torques in the sensor frame and tool frame. The relationship between Fs and Ft is described as follow equation:

$$F_t = {}^T_S T_f \, {}^S F_S = \begin{bmatrix} {}^T_S R & 0 \\ {}^T P_{SORG} \times {}^T_S R & {}^T_S R \end{bmatrix} \bullet F_S = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ R-L_2 & L_1 & 0 & 0 & 0 & 1 \\ 0 & -L_3 & L_2 - R & 1 & 0 & 0 \\ L_3 & 0 & -L_1 & 0 & 1 & 0 \end{bmatrix} \bullet F_S . \quad (2)$$

F_t is our interest forces and torques, but it contains the gravity influence of the grinding tool caused by motion. So the weight of the grinder beyond the force sensor must be compensated for.

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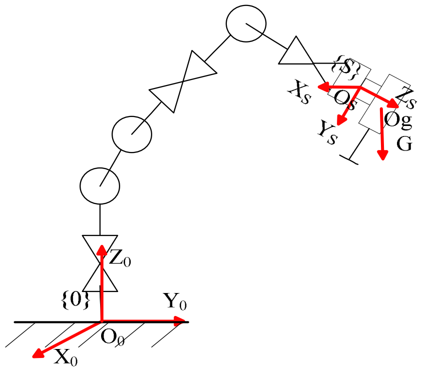

Fig. 4 Schematic diagram of the grinder gravity compensation

Fig. 4 shows a robot with a grinder. {0} is the robot base frame. Og is the grinder head's center of gravity. The gravity compensation of the grinder head is calculated by Equations (3), (4)

$$f_c = f_s - {}^S_0 R G = f_s - {}^0_S R^{-1} G . \quad (3)$$

$$m_c = m_S - P_C \times {}^0_S R^{-1} G . \quad (4)$$

Where f_c and m_c are the forces and torques with the gravity compensation. R is the transformation from the base frame {0} to the sensor frame {S}. From equations: (2), (3) and (4), we get the forces and torques applied at the tip of the tool without the gravity influence. $F_t' = {}^T_S T_f \begin{bmatrix} f_c \\ m_c \end{bmatrix}$.

Simulation and Experiment

In order to implement the force control scheme into the system a simulation is carried out. In the simulation, the matlab R2008a and robotics toolbox 8 are used. Fig. 5 shows the simulation model.

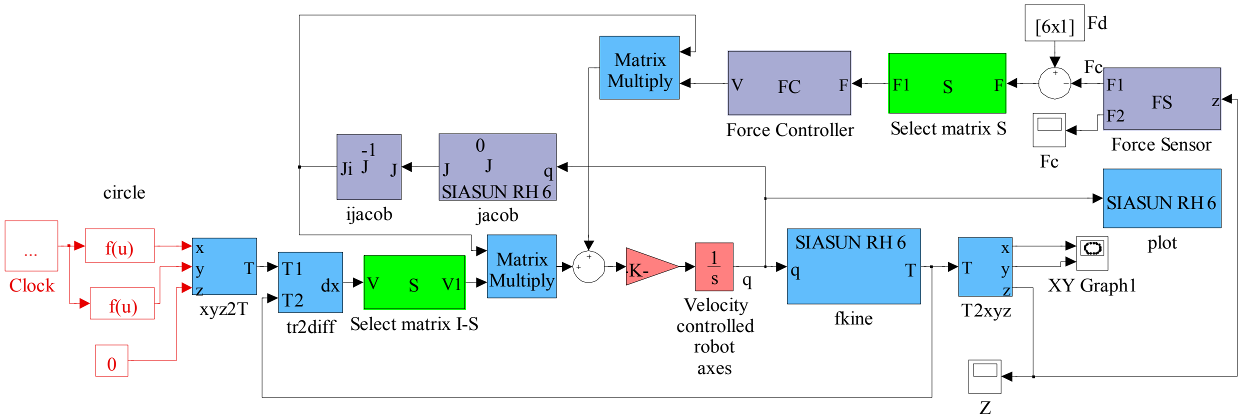

Fig. 5 The simulation model of the force control scheme

In this simulation, we suppose that the robot is in the following state: (a) the grinder of the robot contacts with the workpiece; (b) the force between the grinder and the workpiece is 0; (c) the Z direction position is 0. If the robot moves the tool in Z direction, the force will be detected by the force sensor.

The SIASUN RH6 robot moves the tool in a circle of radius 0.05m in X and Y directions, centered at the point (0.5, 0, 0). The desired force is 2N in Z direction. The robot is modeled by an integrator as a simple velocity servo. Fig. 6 shows the actual tool path of the robot in X and Y directions. We can see that the tracking path in X and Y directions is the desired circle without the influence of the force. Fig. 7 shows the actual force between the grinder and the workpiece. The robot tracks the desired force quickly. In order to remove the frequency interference, a low-pass filter whose cutoff frequency is 5Hz is used. Fig. 8 shows the force data without filter. Fig. 9 shows the force data with a low-pass filter. We can see that the filter can remove the frequency interference effectively.

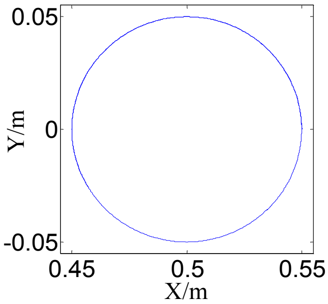

Fig. 6 The tracking result for a circle path

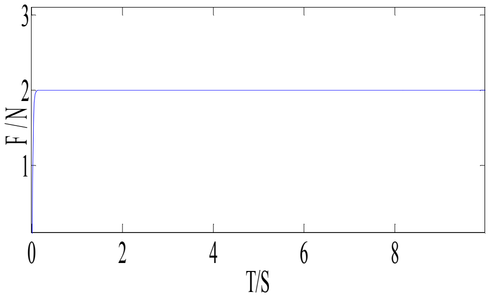

Fig.7 Force between the grinder and the workpiece

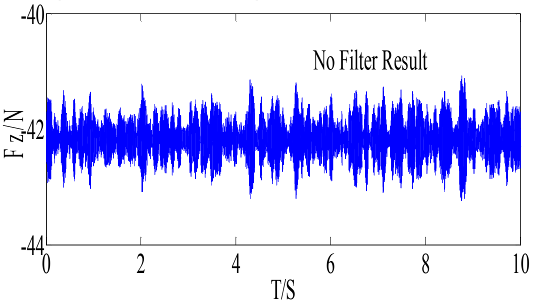

Fig. 8 Force data without filter

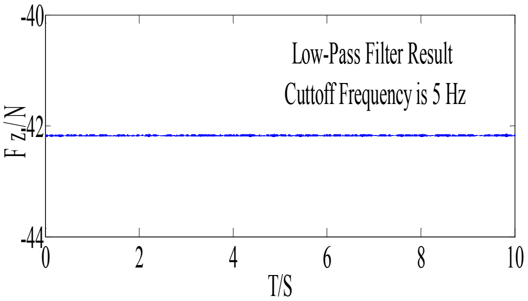

Fig. 9 Force data with a low-pass filter

Conclusions

In this paper, a velocity servo-based hybrid position/force control scheme for a grinding robot is presented. The force data processing and the communication between the force sensor and the robot controller have been discussed. Based on the force and position sensor fusion, the robot is controlled to grind the workpiece in the desired tool path and force using the velocity servo-based strategy. The simulation results illustrate that the developed control scheme is useful for the position and force control. Although we do some work in grinding robot, it is not perfect. Lots of works are left for future research.

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