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Hybrid Position and Force Control of a Robot Arm Equipped with Joint Torque Sensors

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Abstract - A force/torque sensor, which is usually mounted at the wrist of a robot arm, is often used to implement force control. However, this sensor is very expensive and can only measure the forces and moments acting at the end-effector, so it cannot detect collisions occurring at parts other than the end-effector. To deal with these problems, we developed a robot arm in which joint torque sensors are installed at each joint instead of a force/torque sensor. With these torque sensors, hybrid position/force control can be conducted without a force/torque sensor. Experiments were conducted in which a robot arm draws a symbol on a board using a marker attached at the end-effector. These experiments show that position and force control are possible in any direction by using a robot arm with a torque sensor at each joint.

Keywords - Joint Torque Sensor, Force Control, Hybrid Position and Force Control, Impedance Control

1. Introduction

For several decades, a lot of research has been devoted to the development of industrial robots for tasks such as deburring and assembly. Also, recently, much research is being conducted to ensure collision safety during human-robot interaction [1]. Force control is widely used to allow robots to interact with their environments to manipulate objects and perform assembly [2].

A force/torque sensor is often attached at the end-effector of a robot arm to measure the force and moment acting at the end-effector to perform force control [3]. However, force/torque sensors are expensive, and they can only measure the force and moment acting on the parts on which the force/torque sensor is installed. Thus, they cannot be used to detect collisions occurring at the body of a robot arm other than the end-effector. To deal with such a problem, torque sensors can be installed at each joint of a robot arm, which can be used for both force control and collision detection [4]. However, force control using torque sensors shows limited accuracy due to errors in the forces and moments estimated from torque sensors.

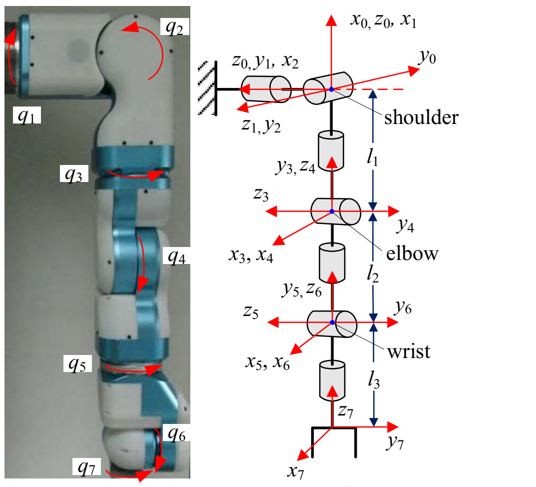
In this study, instead of relying on expensive force/torque sensors, we used joint torque sensors to implement force control. To overcome the limited accuracy and stability of torque sensors, we used a hybrid position and force control scheme. Such a scheme allows the operator to divide the workspace, so that force control is used in some directions for stable contact while position control is used in other directions to compensate for the tracking errors due to the inaccuracy of the torque sensors.

The rest of this study is organized as follows: In section 2, we introduce a robot arm with torque sensors and its control system. In addition, hybrid position and force control in task space are explained. The experimental conditions and the results of a comparative experiment between impedance control and hybrid position and force control are shown in section 3. Finally, section 4 concludes the paper.

2. Robot Arm System

2.1 Mechanical structure of the robot arm

A robot arm developed in our lab is used for this study, which consists of 2 revolute joints for the shoulder, 2 revolute joints for the elbow and 3 revolute joints for the wrist, as shown in Fig. 1(a). At each joint, the joint torque information can be obtained by a joint torque sensor, and velocity-based control is possible with the motor and encoder. The coordinates of the robot arm according to the DH notation, which are used to formulate the control scheme, are shown in Fig. 1(b).



(a) (b)

Fig. 1 Structure of the robot arm: (a) robot arm, and (b) coordinate system.

The joint torque sensor is compact in size so that it can be easily installed at the joint module [5-6]. The joint torque sensor and joint module are shown in Fig. 2.

(a) (b)

Fig. 2 Components of joint: (a) joint torque sensor, and (b) joint module.

2.2 Hybrid position and force control

A control system was developed to realize hybrid position and force control. A control block diagram is shown in Fig. 3 and it should be noted that the algorithm uses the velocity, position, and torque as the feedback. The controller operates with a control period of 15 ms, and RTOS (RTX) is used to guarantee a precise control period.

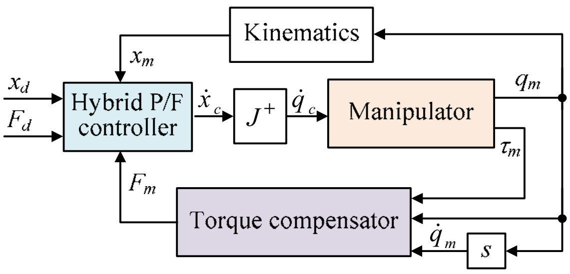


Fig. 3 Control block diagram of the robot arm

For hybrid position and force control, we used a generalized momentum-based observer to estimate the joint torque using the Newton-Euler iterative method. As force control relies on the force/moment feedback to regulate the contact force, the error in torque measurement leads to poor force control performance. To cope with this issue, we used hybrid position and force control. This control scheme uses impedance control for force control, as shown in Fig. 4. The position of the compliance center is important in performing force control in task space. The error in the position of the compliance center leads to the accumulation of error in the moment, which can cause instability when a robot arm comes in contact with the environment.

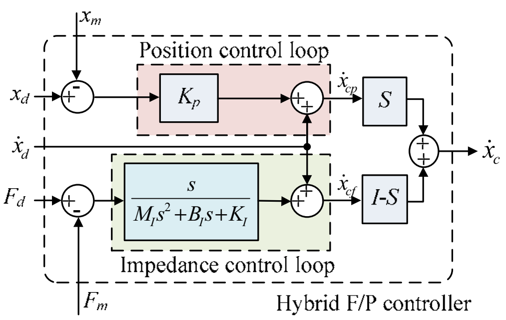


Fig. 4 Control block diagram of hybrid control

The hybrid position and force controller shown in Fig. 4 was used to compensate for possible errors in the estimated forces and moments. Velocity-based impedance control was used in the x-direction to achieve stable contact, while position control was used in other directions. The selection matrix S was used to divide the workspace, and two controllers (i.e., an impedance controller and a position controller) are needed. The position controller is given by

$$\dot{x}_{cp} = \dot{x}_d + K_p(x_d - x_m) \tag{1}$$

where K_p is the position control gain. The impedance controller is described by

$$\dot{x}_{cf} = \dot{x}_d + \frac{s}{M_I s^2 + B_I s + K_I}(F_d - F_m) \tag{2}$$

where M_I, B_I and K_I are the inertia matrix, damping matrix and stiffness matrix of the impedance controller, respectively. It can be seen that the controller converts the interaction force to a velocity command.

3. Experiments and discussion

3.1 Experimental setup

To verify the performance of the proposed method, we prepared an experiment in which the robot arm draws a star on a white board. The experimental setup is shown in Fig. 5. The marker was attached at the end-effector of the robot arm, and the board was set up vertically with an error less than 5 degrees. Also, to ensure stability, we programmed the robot arm so that it stops if the robot arm reaches a singular position. To better demonstrate the effectiveness of the proposed strategy, we conducted a comparative experiment, and we performed drawing based on impedance control and hybrid position and force control.

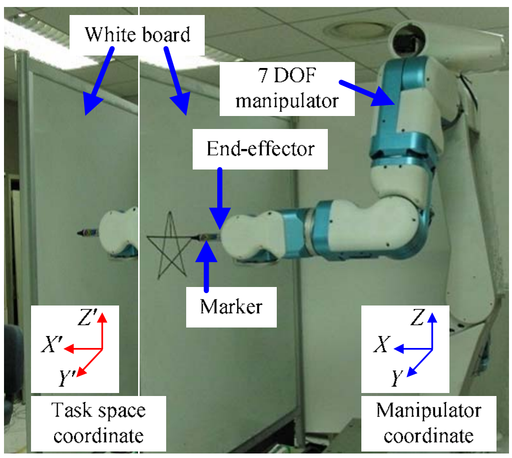


Fig. 5 Experimental setup

To realize stable force control, we must fully understand the desired task. Thus, the desired contact force between the robot arm and the board was set to 5 N considering the compliance of the board. Also, as the board is set up vertically, the robot arm was programmed to maintain contact while performing the task. The task was performed in the following order: contact, drawing the star and pulling the marker away.

3.2 Experimental results

The positioning accuracy of the robot arm was used to evaluate the accuracy of the proposed method. The drawing from the experiment in which an impedance controller was used is shown in Fig. 6. The red line and blue line each represent the desired and measured paths, respectively. The picture in the bottom right corner is a picture of the actual drawing. As can be seen from this result, the robot arm was not able to track the desired path accurately due to force error and friction. The robot arm was to maintain the contact in the x-direction while moving in the y and z directions; however, the force error and the friction in the y and z directions caused a position error of 5 mm. On the other hand, the resulting drawing using hybrid position and force control is shown in Fig. 7. It can be seen that the robot arm was able to track the desired path with the error of 1.5 mm. Also, it was found that the use of the hybrid position and force controller resulted in more stable contact. The results clearly show that in the presence of errors in the measured torque, hybrid force and position control should be used to compensate for such errors.

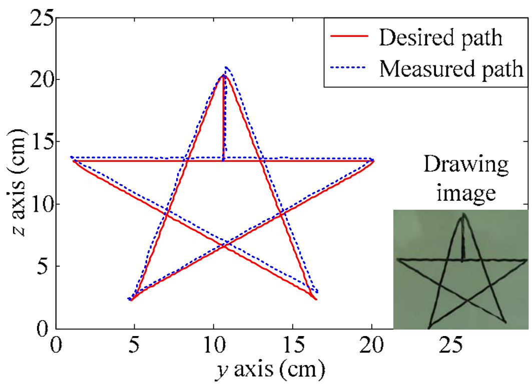


Fig. 6 Experimental result: Impedance control

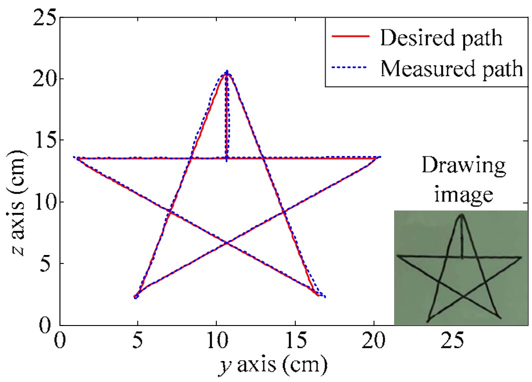


Fig. 7 Experimental result: hybrid control

4. Conclusion

In this study, we proposed a control method using hybrid position and force control to realize effective force control with torque sensors. We compared the results of a star-drawing experiment using impedance control and hybrid control to show the advantages of hybrid position and force control. The following conclusions were drawn from this study:

1. Force control can be realized by utilizing joint torques. Also, hybrid position and force control, which uses either a position controller or force controller depending on the task, can be used to improve the performance of force control using joint torque sensors.
2. Using hybrid position and force control, the robot arm was able to draw a symbol with a positioning accuracy of 1.5 mm and a contact force of 5 N.

The control method proposed in this study allows a robot arm to perform force control without using expensive force/torque sensors. Thus, this method can provide an attractive alternative to robotic force control.

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