Implementation of Torque-based Control on Industrial Robot for Human-Robot Cooperation

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Abstract—Human-robot cooperation is getting important in nowadays factory environments, where safety is one of the most important factors. The use of torque-based controllers is one approach to provide safety and performance in these applications. In this paper, the implementation of torque-based control on industrial robots are presented. First, dynamic properties of the robots, such as inertia and friction parameters, are identified to be used in torque-based controllers. The torque-based controllers are then implemented on an industrial robot, HA020. The performance of torque-based control is demonstrated by the experiments of gravity compensation, joint space control, and the operational space control.

Index Terms—torque-based control, industrial robot, system identification

I. INTRODUCTION

Human-robot cooperation is one of the significant applications in factories for assisting human manipulating heavy loads and teaching the robot complicated tasks. The functionality of human-robot cooperation is typically implemented by installing force sensors to detect the load and human’s intention on an existing position-controlled robot [1]. However, this approach has limitation in safety and performance because it does not provide inherent compliance and does not account for dynamics of the robot [2]. In order to improve the performance and cost of the system, torque-based control has been considered for human-robot cooperation task. One of the main advantages of using torque-based controllers is to improve compliance and utilize the dynamics of the robot [3].

In this paper, implementing torque-based controller on an industrial robot is discussed. The HA020 robot (see Figure 1) is used as a testbed, where only motor specification and DH parameter information were available. Therefore, the robot was disassembled to obtain the dynamic properties of each link of the robot such as mass and inertia of each link [4]. Joint friction is also experimentally identified since compensation of joint friction greatly affects the performance and stability of the robot [5]. With the estimated dynamics properties and joint friction of the robot, the performance of torque-based controllers is evaluated by the following experiments; gravity compensation, joint space control, and the operational space control. The experiment of gravity compensation is to verify the robot’s dynamic properties, and system’s ability to command torque on each joint instead of commanding desired joint angles. The other two experiments are to develop a control scheme for human-robot cooperation. Feasibility of torque-based control on human-robot cooperation system is demonstrated by these experiments.

II. HARDWARE SPECIFICATION

The Hyundai HA020 is a 6-DOF industrial robot, and its total weight is 240kg with a maximum payload of 20kg. The HA020 robot uses AC servo motors with 17bit incremental absolute encoder. The gripper weighting 26kg is attached to the robot, and it assists human robot cooperation. The gripper is controlled via an external control module.(see Figure 1)

The motion control and the servo driver part are modified using the Synqnet-PCI motion controller in order to command torques to individual joints. Instead of the robot’s teaching pendant, the robot can be controlled from Windows based computer with real-time robot control software, called RoboticsLab [6]. Roboticslab has physics-based real-time robot control module and programmable interface that compute the robot’s dynamics and control torques. This

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system uses a RTX(real-time extension) runtime to guarantee deterministic time on Windows platform [6]. Therefore, the readings of the joint angles from the encoder are passed to the RoboticsLab, and the control module in the RoboticsLab computes torques and then commands them to each joint of the robot in real-time.(see Figure 2)

III. SYSTEM IDENTIFICATION

A. Link Properties

System identification of the robot is conducted to obtain the dynamic properties of the robot. In order to calculate dynamics of a robot, the properties of mass, inertia, size, and friction are necessary [7]. (see Figure 3) Since these parameters are not available for HA020, the robot is disassembled to obtain the mass and the center of mass of each link. With the measured values, the moment of link inertia is estimated by a 3D model. In addition, rotor inertias are obtained from the specification of each motor and accounted for in the dynamic model [8].

B. friction compensation

The industrial robot has large joint frictions due to the use of large motors and high gear-ratio. Therefore, high gains are typically applied to compensate for the large joint frictions in controlling the robot motion. This may adversely affect on the system’s flexibilities, time delays, and sampling rate. In implementing torque-based control, the Coulomb and viscous friction models are used and its parameters are estimated to compensate for the friction directly. The theoretical friction compensation torque \( \tau_{fric} \) is

\[
\tau_{fric} = f_c \text{sign}(\dot{q}) + f_v \dot{q}
\]  

where \( f_c \) and \( f_v \) are Coulomb and viscous friction parameters, respectively.

In practice, the direction and magnitude of \( \tau_{fric} \) may change frequently and abruptly when the joint velocity, \( \dot{q} \), is near zero. Another problem with the friction compensation is when the robot starts to move. When the velocity of the joint is zero, the direction of Coulomb friction cannot be determined. Due to this problem, the robot cannot start to move until the position error accumulate to a large value. Once the robot begins to move, it overshoots the desired trajectory. To overcome these problems, the friction compensation torque is designed as the following when the joint velocity is below a certain threshold, \( \dot{q}_t \). In order to determine the direction of friction compensation torque in the region of \( |\dot{q}| < \dot{q}_t \), the desired input torque, \( \tau \), is used. If the command torque, \( |\tau| > |\dot{q}_t| \), Coulomb and viscous frictions are applied. In the region of \( |\tau| < |\dot{q}_t| \) region, the friction compensation torque is linearly interpolated based on the desired command torque, \( \tau \). (see Figure 4)

\[
\tau_{fric} = \begin{cases} 
  f_c \text{sign}(\dot{q}) + f_v \dot{q} & \text{if } |\dot{q}| \geq \dot{q}_t \\
  f_c \text{sign}(\tau) + f_v \dot{q} & \text{if } |\tau| \geq |\dot{q}_t| \\
  f_c \frac{\tau - f \text{sign}(\tau)}{\dot{q}_t} + f_v \dot{q} & \text{if } |\tau| < |\dot{q}_t|
\end{cases}
\]

IV. CONTROL FRAMEWORK

To evaluate the performance of the torque-based controllers, the joint space control and the operational space control are implemented.

A. Joint space control

The dynamics of the robot in joint space is described by [9]

\[
A(q)\ddot{q} + b(q, \dot{q}) + g(q) = \Gamma,
\]

where \( A(q) \), \( b(q, \dot{q}) \), and \( g(q) \) are the inertia matrix, Coriolis/centrifugal torques, and gravity torques, respectively. Dynamic decoupling is achieved by using the control structure

\[
\Gamma = \hat{A}(q)\Gamma^* + \hat{b}(q, \dot{q}) + \hat{g}(q),
\]

where, \( \hat{A}(q), \hat{b}(q, \dot{q}), \) and \( \hat{g}(q) \) present the estimates of \( A(q), \) \( b(q, \dot{q}), \) and \( g(q) \). The term, \( \Gamma^* \), is the input for the decoupled control, which is composed with PD control. In addition, the feed-forward compensation torque is added for friction.

B. Operational space control

The dynamic behavior of a manipulator in the operational space is specified as follows [9]

\[
\Lambda(x)\ddot{x} + \mu(x, \dot{x}) + p(x) = F,
\]

where \( \Lambda(x), \) \( \mu(x, \dot{x}), \) and \( p(x) \) are the inertia matrix, the Coriolis/centrifugal forces, and gravity forces in the operational space, respectively. The control force, \( F \), in (6), can be composed to provide a decoupled control structure by choosing

\[
F = \hat{\Lambda}(x)\dot{x}^* + \hat{\mu}(x, \dot{x}) + \hat{p}(x),
\]
where, \( \hat{\Lambda}(x), \hat{\mu}(x, \dot{x}), \text{ and } \hat{\rho} \) represent the estimates of \( \Lambda(x), \mu(x, \dot{x}), \text{ and } p(x) \). The term, \( f^* \), is the input for the decoupled control. In order to achieve the desired motion in the operational space, a linear dynamic behavior can be composed with a PD controller of the form

\[
f^* = k_p(x - x_d) - k_v(\dot{x} - \dot{x}_d),
\]

where, \( x_d \) and \( \dot{x}_d \) are the desired position and velocity of the end-effector, respectively. \( k_p \) and \( k_v \) are the position and velocity gains. Once \( f^* \) is determined, \( \Gamma \) can be produced by

\[
\Gamma = J^T F,
\]

where, \( \Gamma \) and \( J^T \) are the command torque and the transpose of Jacobian matrix, respectively. The command torque is applied to the robot with the feed-forward compensation torque for friction.

V. EXPERIMENTAL VALIDATION

Experiments have been conducted to demonstrate the friction compensation, gravity compensation, joint space control and the operational space control. The servo rate of the controller of the robot is set to 500Hz. For trajectory tracking, incremental displacements are specified using cubic spline algorithm at each control cycle. For the velocity feedback, measured angles from encoders are fed to a low-pass filter with a cutoff frequency of 10Hz.

A. Friction Compensation

Figure 6 compares the results between command torque and friction-compensated command torque for the first joint axis when the robot starts to move using the joint space control. According to Equation (1), the compensated torque is interpolated in \( |\dot{q}| < \dot{q}_i \) region. The dotted line shows the boundary of \( |\dot{q}| = \dot{q}_i \). With this compensation for friction, the robot was able to start smoothly without too much overshoot, which can be seen in the experiment of joint space control.
B. Gravity Compensation

The gravity compensation is to verify whether the system is able to command torque to each joint instead of commanding desired joint angles. Also, it is to validate if the robot can show compliant motion using the torque-based control.

Before applying gravity compensation torque, the robot could not support its own weight. Figure 5 shows the gravity compensation experiment. The robot is compliant to the applied forces by the operator. From the experiment, it is verified that the torque-based controller effectively compensates for the gravity using the estimated dynamic parameters of the robot and the robot is able to perform the compliant motion.

C. Joint Space Control

All links are set to run a sinusoidal trajectory at a period of 8 seconds and at an amplitude of 15 degrees. Figure 7 shows the responses of the 4th joint axis. It shows the result of tracking performance of the joint. The maximum absolute error is 0.0243 radian during the experiment.

D. Operational Space Control

The experimental results of the operational space control is plotted in Figure 8. The robot is commanded to move 0.10 meters along the x-axis. The maximum absolute error is 0.0044 meters during the experiment.

E. Discussion

The above experiments demonstrate the feasibility of the torque-based control on an industrial robot for human-robot cooperation. The gravity compensation, the joint space control, and the operational space control are successfully implemented. However, the tracking performance of the joint space and the operational space control shows the rooms to be improved further. The friction does not seem to be well compensated in this study due to the insufficient modeling and its parameter estimations. It is believed that improvement on the friction compensation will greatly improve the performance of these torque-based controllers on industrial robots.

VI. Conclusion

This paper presents an implementation of torque-based controller for the industrial robot, HA020. Dynamic parameters have been identified by disassembling the robot and the friction parameters are estimated through experiments. These parameters were experimentally validated through the gravity compensation controller. Once dynamic parameters are verified, the gravity compensation, the joint-space control, and the operational space control are implemented. The experimental results demonstrate the capabilities of torque-based control on industrial robots. This torque-based control is expected to be useful in human-robot cooperation in providing compliance and high performance.

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