Force Sensor-less Workspace Virtual Impedance Control Considering Resonant Vibration for Industrial Robot

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Keywords: disturbance observer, D-PD control, feedforward inverse-dynamic torque compensation, impedance control, external force estimation, two-inertia model

Force sensor-less impedance control with motion-based inner loop control is proposed. The dynamic model of the manipulator is utilized with the disturbance observer to estimate the interaction between robot and the environment. The workspace virtual impedance model is implemented by using the estimated external force with the feedback linearization to compensate for gravity and friction terms. Hence, the impedance behavior of the end-point is implemented independent of the dominant dynamics of the manipulator. In this paper, the feedback compensation scheme utilizes the estimated load-side angular speed $\hat{\omega}_L$ from the state observer to calculate the gravity and friction terms. This scheme is a new concept. This load-side angular speed is also utilized in the external force estimation. Furthermore, the resonant vibration characteristic of the flexible joint is suppressed by the cascaded speed control loop with full state feedback. The resonant suppression is then considered both in the motion control mode and impedance control mode. This control method is also a new concept for impedance control. Fig. 1 depicts the inner motion feedback control system of each joint with the impedance control in workspace. Both interface position and speed from impedance control are used to implement the virtual impedance model by inner-loop robust D-PD control. A new implementation of workspace impedance control is straightforward in comparison with the method using only position reference in ordinary inner-loop PD position control.

To implement the 3-DOF impedance control scheme when robot contacts with the operator, first, the third joint of robot moves to rest at $-\pi/2$ rad without any constraint. Next, the operator exerts force at the end-point of the robot along the X direction of the base coordinate frame. The robot then responds to the external force complying with its impedance model. The experimental results in Fig. 2 show the compliant motion of the robot along the X direction of the base coordinate frame. The robot then responds to the external force. The additional experiment based on force sensor is carried out to confirm the validity of the force sensor-less impedance control. When robot has interaction with the operator, the operator must apply force directly to the force sensor to make the robot percept the external force correctly. With same experiment as aforementioned, the operator exerts force at the force sensor mounted on end-point of the robot along the X direction of the base coordinate frame. Experimental results in Fig. 3 are almost the same results when comparing with the results from the force sensor-less impedance control experiment. Moreover, the external force estimation scheme gives the reasonable good signal when comparing with the signal from force sensor.
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The motion control paradigm provides sufficient performance in many elementary industrial tasks. However, only stiff motion the robot cannot accommodate the interaction force under constrained motion. In such situation, the robot is required to perform interaction behavior with the environment. The conventional impedance control schemes require force-sensing devices to feedback force signals to the controllers. The force-sensing device is therefore indispensable and the performance of the system also depends on the quality of this device. This paper proposes a novel strategy for force sensor-less impedance control using disturbance observer and dynamic model of the robot to estimate the external force. In motion task, the robust D-PD (derivative-PD) control is used with feedforward inverse-dynamic torque compensation to ensure robustness and high-speed response with flexible joint model. When robot is in contact with environment, the proposed force sensor-less scheme impedance control with inner-loop D-PD control is utilized. D-PD control uses both position and speed as the references to implement the damping and stiffness characteristic of the virtual impedance model. In addition, the gravity and friction force-feedback compensation is computed by the same dynamic model, which is used in external force estimation. The flexible-joint robot model is utilized in both disturbance observer and motion control design. The workspace impedance control for robot interaction with human operator is implemented on the experimental setup three-degree-of-freedom (3-DOF) robot manipulator to assure the ability and performance of the proposed force sensor-less scheme for flexible-joint industrial robot.

Keywords: disturbance observer, D-PD control, feedforward inverse-dynamic torque compensation, impedance control, external force estimation, two-inertia model

1. Introduction

The increasing use of robot in industrial society arouses the continuous development in advanced motion control. High path tracking accuracy with fast motion is the main objective of the researches. Several motion control schemes for industrial robot have been introduced (1)–(3). Among these literatures, the control schemes dealing with flexible joint model of the robot have been verified to be efficient for industrial robot equipped with harmonic drive (3)–(5). When the robot is implementing the task, the robot may come into the unexpected collision with a human operator or a work piece. In this case, only fast motion control strategy, which makes the robot much stiffer than the environment, cannot accommodate the interaction between robot and environment. The approach to control robot with considering the interaction with the environment is required to manipulate the dynamic relation between the interaction state variables (e.g., position, velocity, and force) as illustrated in Fig. 1. The relation is described by the equivalent mechanical components, and in the workspace, it is usually represented by virtual mass M_v, damper D_v, and spring K_v. Impedance control (7) has been introduced to control the dynamics of interaction or external force from the environment F_{ext} and the state variables. The objective is to realize a desired dynamic relationship between end-point position and interaction force. However, several strategies appeared in the literatures on impedance control for industrial robot depend on the use of force sensing device to detect the interaction force (6)–(9). Based on these strategies, it is nearly impossible to detect the collision occurred on the manipulator structure. Consequently, the use of the additional sensory device to detect the interaction force is difficult and ineffective in practical cases. Recently, the new actuator systems embedded in the structure of the robot to accommodate the external force have been proposed (10)(11). However, these approaches need to design all new structure of the robot, and they cannot be implemented in the ordinary industrial robots.
Unlike the previous direct-coupling model based torque observer (12), this paper utilizes both the disturbance observer based on two-inertia model and the dynamics equation of the robot in order to estimate the interaction force between the robot and the environment. Moreover, the feedforward inverse-dynamic torque compensation scheme used in motion control mode is switched to the feedback compensation scheme in impedance control mode with the same computation program for the robot dynamics equation in both control modes. This is the new technique for implementing with the actual system. In impedance control mode, the estimated load-side angular speed is utilized to calculate the gravity and friction terms. The new approach for feedback linearization by using the estimated load-side angular speed to eliminate the gravity and friction terms of the robot is introduced in this paper. With D-PD control, the proposed impedance control scheme is able to employ the estimated interaction force to regulate both the position and speed references complying with the virtual impedance characteristic during the contact condition. With using both position and speed references, the achievement of the impedance model dynamics with D-PD control is proved to be better than the impedance model implemented with conventional PD control.

2. Workspace Impedance Control with Robust D-PD Control

The concept of active control of a manipulator's interactive behavior is formally treated as an aspect of impedance control (7). The impedance control is aimed at realizing a desired dynamic relationship between end-point motion (i.e., position, velocity, and acceleration) and contact force. In this paper, the impedance behavior of the robot end-point is chosen as

\[ F_{\text{ext}} = M_{\text{ff}} \ddot{X}_{\text{int}} + D_{\text{ff}} \dot{X}_{\text{int}} + K_{\text{ff}} X_{\text{int}} \]  

where the parameters \( M_{\text{ff}}, D_{\text{ff}}, \) and \( K_{\text{ff}} \) are respectively, mass, damping, and stiffness of the desired virtual mechanical impedance model between the end-point position error \( X_{\text{int}} \) and the external force \( F_{\text{ext}} \). To implement the high bandwidth impedance control, the decoupled joint acceleration control scheme is required. This control scheme can implement the high bandwidth for ideal impedance model as illustrated in Fig. 2.

However, the motion control system of industrial robot is generally based on a cascaded control scheme, which is built up by nesting the position control system with minor speed control loop and minor current control loop. Therefore, it is difficult for industrial robot to implement the virtual impedance model with acceleration control scheme. The most common position control for industrial robot is the simple PD control, which is sufficient for robot with rigid and elastic joint model (13). In Fig. 3, the joint-space interface motor position \( \theta_{\text{Min}} \) is derived from the load-side position \( \theta_{\text{Con}} \) multiplied with gear ratio \( R_g \). This interface motor position is used to implement the impedance control to the conventional PD position control. Therefore, there is only joint-space interface load-side position \( \theta_{\text{Con}} \) used to regulate only position command in the joint-space position control system. Hence, the dynamic of impedance model cannot be implemented completely. The inverse kinematics scheme is used to transform the end-effector position in workspace coordinate to joint-space components. The inverse kinematics transformation \( T^{-1} \) is used to compute the inverse kinematics problem (15). The workspace position response from the impedance model is transformed to joint-space position command and is implemented in the position control loop to realize the desired impedance characteristic of the robot. Moreover, implementing the workspace impedance control with the conventional PD control requires the complex inverse kinematics calculation. This burdened computation may be solved by numerical algorithm (15), however, it is time-consuming and difficult to carry out quickly.

In this paper, the previous proposed D-PD position control scheme (13-15), which gives fast response, is utilized to implement both damping and stiffness of the virtual impedance model.

Consequently, implementing the workspace impedance control with the new D-PD control scheme utilizes both speed and position outputs from the inverse Jacobian \( J^{-1} \). In addition, the inverse Jacobian matrix \( J^{-1} \) is used to transform the differential relationship between the joint-space
interface angular position $\theta_{int}$ and workspace end-point position error $X_{int}$. The motion of the robot in workspace is resolved into its joint-space components through the inverse Jacobian matrix. The initial condition supplied with the inverse kinematics ensures that the joint-space angular position $\theta_{int}$ and the workspace position $X_{int}$ correspond to the same physical point at the time of starting the impedance control. Consequently, implementing the workspace impedance control with the new D-PD control scheme utilizes both speed and position command from the impedance model output. Comparing Fig. 3 to Fig. 4, the difference in controller structure in Fig. 4 for industrial robot.

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$$
\begin{align*}
\mathbf{A} &= \begin{pmatrix}
-A_d & I_m & 0 & 0 \\
0 & -\frac{K_p}{J_m} & -\frac{K}{J_m} & 0 \\
\frac{1}{K_v} & 1 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}, \\
\mathbf{b} &= \begin{pmatrix}
\frac{K_s}{J_m} \\
0 \\
\frac{1}{K_v} \\
0
\end{pmatrix}, \\
\mathbf{c} &= \begin{pmatrix}
-1 \\
0 \\
0 \\
0
\end{pmatrix}
\end{align*}
$$

where $\theta_M$ is the angular position of actuating motor, $\theta_L$ is the angular position of the gear-output side robot link, $\theta_S$ is the torsional angular position, and $\tau_L$ is the step-wise disturbance torque. The compact form of this state equation can be represented by

$$
\dot{x} = (\mathbf{A} - \mathbf{K}_s \mathbf{A}_1) \omega_M + \mathbf{A}_2 \omega_M + \mathbf{B}_1 \mathbf{F}_{cmd}.
$$

The nominal values of link inertia $J_L$ and gear coupling stiffness constant $K_s$ are easily identified by resonant and anti-resonant characteristic of the robot arm. Based on the values of motor inertia $J_M$, torque constant $K_T$, and gear ratio $R_g$, Damping coefficient or viscous friction is represented by $D_M$ and $D_L$ for motor side and gear-output side, respectively. In practice, the value of $D_M$ is small when comparing with the viscous friction of load side at the coupling gear; therefore, $D_M$ is assumed to be zero and viscous friction of the system is the load-side friction ($D_L$). The step-wise load disturbance torque $\tau_L$ is estimated by using the augmented minimum state-observer equation of the two-inertia model

$$
\dot{x} = \mathbf{A} \omega_M + \mathbf{B}_1 \mathbf{F}_{cmd}.
$$

where $x$ is the observer state variable vector. The observed states of the system are represented by $\hat{x}$, i.e., $\hat{\omega}_L$, $\hat{\omega}_S$, and $\hat{\tau}_L$. The matrices $\mathbf{A}_1$, $\mathbf{A}_2$, $\mathbf{A}_2$, and scalars $A_1$, $B_1$ are defined according to the system in (7). The observer gains $\mathbf{K}_s$ are chosen so that the state-observer equation is stable and gives fast response. When the robot has interaction with the environment, the disturbance torque $\tau_L$ of the robot system is generally interpreted as

$$
\tau_L = \tau_{merr} + \tau_{col} + \tau_{grav} + \tau_{fric} + \tau_{ext}.
$$

The disturbance torque of the system is then composed of the disturbance from internal robot dynamic model and the disturbance from external interaction with environment. The interaction with environment causes external torque $\tau_{ext}$ exerting on the robot. The robot dynamic torque comprises the torque from inertia variation and the coupling torque term $\tau_{merr}$, the centrifugal and Coriolis term $\tau_{col}$, the gravity term $\tau_{grav}$, and the friction term $\tau_{fric}$.

The output load torque $\tau_L$ for driving in the gear output side is the summation of robot dynamics, including nominal term in output side of the two-inertia model, and the external


![Diagram of robot dynamics and control system](image)

Fig. 5. External force estimation from disturbance observer and robot dynamics calculation

The output load torque of the system can be derived as shown in (10).

\[
\tau_L = \tau_{dyna} + \tau_{ext} = H(\theta_L)\dot{\theta}_L + D_L\dot{\theta}_L + b(\theta_L, \dot{\theta}_L) + c(\theta_L) + f(\theta_L) + \tau_{ext} \,
\]

The dynamics of robot involves inertial moment \(H(\theta_L)\), centrifugal and Coriolis vector \(b(\theta_L, \dot{\theta}_L)\), gravity vector \(c(\theta_L)\), viscous friction term \(D_L\dot{\theta}_L\), Coulomb friction term \(f(\theta_L)\), and external torque from the environment. The nominal torque \(\tau_{L_n}\) in (11) relates to the nominal link inertia and the nominal viscous friction of the two-inertia model. Therefore, the disturbance term for system is derived in (12). All the dynamics terms should be calculated by using load-side angular position. Hence, it is reasonable to derive from the estimated angular speed \(\hat{\omega}_L\) from the observer.

\[
\tau_{L_n} = J_{L_n}\ddot{\theta}_L + D_{L_n}\dot{\theta}_L + b(\theta_L, \dot{\theta}_L) + c(\theta_L) + f(\theta_L) + \tau_{ext} \,
\]

By using the estimated external torque \(\hat{\tau}_L\) from the observer, the estimated external torque \(\tau_{ext}\) exerted by the environment on the manipulator is then calculated by (13). By employing only information of motor current and rotor position, the external torque can be estimated with straightforward algorithm. Thus, the external force in workspace is calculated in (14) by using inverse-transpose Jacobian matrix \(J^T_w\). The block diagram in Fig. 5 illustrates the structure of the estimation of external force \(\hat{F}_{ext}\). The discrete form of integration and differentiation in Fig. 5 is used to regenerate the estimated load-side position response \(\hat{\theta}_L\) and load-side acceleration response \(\hat{\omega}_L\) from the state observer output signal. The integrator is normally used to resolve for the position response in two-inertia model\(^{35,36}\). In practice, there is no computational error from DSP (Digital Signal Processing) based system and no deviation of the estimated value. Moreover, with the connection of the estimated external force \(\hat{F}_{ext}\) and the impedance control, the overall closed-loop system will generate the stable response. In case of the constant external force, the actual load-side speed \(\hat{\omega}_L\) and the estimated load-side speed \(\hat{\omega}_L\) of the robot will converge to zero. The regenerated load-side position \(\hat{\theta}_L\) will also converge to a constant value. The initial value of \(\hat{\theta}_L\) is the value of the position command at the point that the control system is switched to impedance control.

\[
\hat{\tau}_{ext} = \tau_L - H(\dot{\theta}_L) - J_{L_n}L_n + b(\hat{\theta}_L, \hat{\omega}_L)
\]

\[
\hat{\dot{\theta}}_{ext} = J^T_w \hat{F}_{ext}
\]

4. Impedance Control With Internal D-PD and Feedforward Inverse-dynamic Torque Compensation Scheme

Generally in impedance control of the robot, the simple equivalent physical network illustrates a single-axis manipulator connected to an environment with admittance causality and can be represented by the bond graph\(^{37,38}\). The impedance coupled to the common-effort junction of the bond graph with the command source represents the relation between force and motion. These force and motion are commanded by the controller, and have both static and dynamic force/displacement relation. In this paper, the impedance behavior of the robot end-point is chosen as the aforementioned relation expressed in (1).

Force sensor-less impedance control with motion-based inner loop control is proposed in this paper. The dynamic model of the manipulator is utilized with the disturbance observer to estimate the interaction between robot and the environment. The workspace virtual impedance model is implemented by using the estimated external force with the feedback linearization to compensate for gravity and friction terms. Hence, the impedance behavior of the end-point is implemented independent of the dominant dynamics of the manipulator. In this paper, the feedback compensation scheme utilizes the estimated load-side angular speed \(\hat{\omega}_L\) from the state observer to calculate the gravity and friction terms. This scheme is a new concept. This load-side angular speed is also utilized in the external force estimation. Furthermore, the resonant vibration characteristic of the flexible joint is suppressed by the cascaded speed control loop with full state feedback. The resonant suppression is then considered both in the motion control mode and impedance control mode. This control method is also a new concept for impedance control.

The total control scheme in Fig. 6 depicts the inner motion feedback control system of each joint with the impedance control in workspace. The alternative implementation of the impedance control scheme in joint space with inner-loop robust D-PD control scheme has been proposed\(^{18}\). The feedforward inverse dynamic torque compensation is used in this robust D-PD control scheme. The feedforward compensation utilizes the future value of the position reference to compute the robot dynamic disturbance torque of the system. The load-side position \(\theta_e\) is calculated from motor-side position reference \(\theta_{ref}^m\) by using the transfer function \(W_{r-t}(\cdot)\). The computed disturbance torque from the dynamic model is then transferred to the compensation current \(I_{comp}\) by using transfer function \(T_m(\cdot)\). In this paper, both interface position and speed from impedance control are used to implement...
the virtual impedance model by inner-loop robust D-PD control. A new implementation of workspace impedance control is straightforward in comparison with the method using only position reference. Moreover, the latter method requires a complicated technique to solve the inverse kinematics for position reference in the joint space. To directly solve the position in joint space from the position in workspace, the complex mathematical algorithm to deal with the inverse Jacobian matrix \( J^{-1} \) is unavoidable.

The sampling rate \( (T_s) \) used in the control program is same for impedance control and inner-loop position control at 200 µs. The switch on/off block in Fig. 6 is used for switching the control signal between motion control mode in unconstrained environment and impedance control mode when robot has interaction with environment. The specific threshold value is used for decision of the large load torque exerting to the robot. The threshold value for large load torque is determined depending on the parameter variation of the robot and the error of the robot dynamics model in external force estimation scheme. In case of the experimental setup used in this paper, the variation of the estimated external torque in joint-space \( \hat{\tau}_{\text{ext}} \) due to the error of the robot dynamics model and the parameter variation is not more than 20% of the nominal value. Hence, the threshold value for the switch on/off is set at the 20% of the nominal torque value for each joint.

After the large load torque is detected from the external torque estimation scheme, the switch on/off block will switch the motion control mode to impedance control mode. At the moment of switching, the position reference \( (\theta^M) \) will be held and the speed reference \( (\omega^M) \) will be reduced to zero. The impedance model will generate position and speed reference instead. Moreover, the feedforward dynamic torque compensation is switched into feedback dynamic torque compensation. Hence, the safety in collision is fulfilled during the high performance task operating in the unconstrained environment before the collision.

5. Experimental Results

The implementation of the proposed control scheme is carried out with the experimental setup 3-DOF robot manipulator system. The system consists of the robot manipulator with harmonic drives installed in each joint with identical gear ratio of 160. In this system, all computations are performed by TMS320C6701 DSP (Digital Signal Processor) based system. The motor position and the torque current are the available information. Kinematics model of the robot with Cartesian coordinate in each joint is shown in Fig. 7. The kinematics model parameters and actuator parameters of the experimental robot are listed in Table 1 and Table 2. The model of Coulomb friction \( f(\theta_i) \), is identified by gradually applying the current command to the motor driver and recording the speed response of the motor that corresponds to the current command. The current at the moment that motor is starting to move is used to determine the Coulomb friction of the system.

Three types of experiments are carried out to verify the proposed approach. First, the impedance characteristic test is carried out by using the generated force signal. Next, the force sensor-less robot interaction with operator in workspace is implemented and finally the force sensor based impedance control is executed by employing the force sensor mounted on the end-point of the robot to validate the efficiency of the proposed force sensor-less scheme. In the experiment, the minus value of the force signal means the force...
Fig. 7. Kinematics model of the experimental 3-DOF robot manipulator

Table 1. Kinematics model parameters of the experimental setup robot

<table>
<thead>
<tr>
<th>Robot arm length and offset</th>
<th>Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>l₁₀</td>
<td>216.5</td>
</tr>
<tr>
<td>l₁₁</td>
<td>156.0</td>
</tr>
<tr>
<td>l₁₂</td>
<td>214.0</td>
</tr>
<tr>
<td>l₂₁</td>
<td>560.0</td>
</tr>
<tr>
<td>l₂₂</td>
<td>625.0</td>
</tr>
</tbody>
</table>

5.1 Workspace Impedance Characteristic Test

For 3-DOF impedance characteristic test, the force signals in X, Y, and Z direction of the base coordinate frame are generated and used as the input signals to the workspace impedance model. The impedance control deals with the force signals to generate the robot motion that accommodates the external force signals. Parameters of two impedance models in each coordinate of the workspace are shown in Table 3 and Table 4.

The robot is set up to be low stiffness in the X direction and equally high stiffness with heavy virtual mass in Y and Z direction of the base coordinate frame. The equal forces at 10 N are generated along three axes. First, the robot moves with only the third joint (Joint3) from home position, which all joints are at 0 rad, to the point that Joint3 is at $-\pi/2$ rad. After that, the pulse force signals are generated to the control system serving as the external force exerted on the end-point of the robot.

The experimental results in Fig. 8 and 9 show the different dynamic responses in X direction according to the different virtual impedance model in that axis. The impedance characteristic is set to that only the bandwidth is different. The bandwidth for impedance model No.2 is 5 times faster than that of the impedance model No.1. With the same virtual impedance model in Y and Z direction, the same dynamic responses are obtained. The robot is well accommodate the external force in the X direction when compares with Y and Z direction which the impedances are stiffer than that of X direction.

5.2 Robot Interaction with Operator in Workspace

To implement the impedance control scheme when robot...
contacts with the operator, the operator exerts force at the end-point of the robot along the X direction and then in the Y direction as shown in Fig. 10. The robot then responds to the external force, which is estimated from the proposed scheme, according to its impedance model. The virtual impedance model is set up by using the parameters in Table 3. The experimental results in Fig. 11 show the dynamic responses of the robot against the external force from the operator in X and Y direction. The additional experiment based on force sensor is carried out to confirm the validity of the force sensor-less impedance control scheme. The force sensor is mounted on the end-point position of the robot. When robot has interaction with the operator, the operator must apply force directly to the force sensor to make the robot percept the external force correctly. This is one weak point of the force sensor based scheme.

With same experiment as aforementioned in the force sensor-less scheme experiment, the robot interacts with the operator at the pose shown in Fig. 10. The operator exerts force at the force sensor mounted on end-point of the robot along the X direction and then along the Y direction. The impedance model is set up same as the force sensor-less scheme experiment. Force signal from the force sensor is processed and filtered to reduce the high frequency noises. The force signal from force sensor is used in the impedance control scheme instead of signal from the external force observer. The experimental results in Fig. 12 show results like the previous force sensor-less impedance control experiment. Thus, the effectiveness of the force sensor-less impedance control is confirmed.

6. Conclusion

The implementation of force sensor-less impedance control based on disturbance observer and dynamics computation of the robot is proposed. With the equal gain $K_{pd}$ and $F_{pd}$ in D-PD position control scheme, the impedance model is well realized with characteristics closed to the system with acceleration control scheme. The feedback linearized compensation by using the robot dynamic model computation and the observed angular speed of the link guarantees the elimination of the dynamic effect of the robot during impedance control.

From the experimental results, the proposed force sensor-less impedance control strategy effectively detects the external force with fast response. Unlike the robot using force sensor, the external force from environment can exert on any part of the robot structure without restriction when utilizing the proposed force sensor-less scheme. With inner D-PD position control, the dynamics of impedance model is analytically superior to the application with conventional PD position control. The results from the experiments confirm that the impedance control based on the external force estimation achieves the fast detection of the external force exerting on any parts of the robot. In addition for utilizing the force sensor-less scheme, the acceleration control with disturbance observer is required to realize the high-bandwidth implementation for both motion and impedance control.

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References


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