High-performance Load Torque Compensation of Industrial Robot using Kalman-filter-based Instantaneous State Observer

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Robust motion control against dynamic torque is required for rapid and precise motion control of industrial robots. In this regard, a disturbance observer (DOB) is widely used to achieve robust motion control. In general, it is difficult to achieve robust motion control against a step load torque because the DOB exhibits an estimation delay. To overcome this problem, this paper proposes a new method involving the use of a Kalman-filter-based instantaneous state observer for load torque compensation. The proposed method achieves the instantaneous load torque estimation of a two-inertia system using a load-side acceleration sensor. Torque compensation based on instantaneous torque estimation is highly robust against the insertion of a step load torque. The effectiveness of the proposed method is confirmed by performing both a numerical simulation and experiments using an industrial robot arm.

Keywords: industrial robot, two-inertia system, load torque estimation, acceleration sensor

1. Introduction

Industrial robots are required to operate with high-speed and high-precision to improve the productivity and quality. To meet these requirements, it is essential to achieve robust motion control of industrial robots against a dynamic torque.

To achieve robust motion control, a disturbance observer (DOB) is widely used in industrial field. In general, it is difficult to achieve high robustness against an insertion of a step load torque because the DOB exhibits an estimation delay attributed to pole allocation. Katsura et al. have proposed a position-acceleration integrated disturbance observer (PAIDO) as a high-performance DOB (1). However, it is difficult to apply PAIDO to a two-inertia system such as a robot arm with a reduction gear, because PAIDO is intended for one-inertia system.

To overcome this problem, this paper proposes a method involving the use of Kalman-filter-based instantaneous state observer (KFISOB) for the instantaneous torque estimation of a two-inertia system. The proposed method achieves instantaneous load torque estimation of a two-inertia system using a load-side acceleration sensor. Load torque compensation based on the instantaneous torque estimation is highly robust against the insertion of the step load torque. The effectiveness of the proposed method is confirmed by performing both a numerical simulation and experiments using an industrial robot arm.

2. Load Torque Estimation using Kalman-filter-based Instantaneous State Observer

2.1 Instantaneous State Observer using Load-side Acceleration

The state equation of a two-inertia system including the load torque \( \tau_L \) is expressed as follows.

\[
\frac{d}{dt} \begin{bmatrix} \hat{\omega}_M \\ \hat{\omega}_L \\ \theta_S \end{bmatrix} = \begin{bmatrix} \frac{D_{Mn}}{J_{Mn}} & 0 & \frac{K_{Sn}}{R_{gn}}J_{Mn} \\ 0 & \frac{D_{Ln}}{J_{Ln}} & \frac{K_{Sn}}{J_{Ln}} \\ \frac{1}{R_{gn}} & -1 & 0 \end{bmatrix} \begin{bmatrix} \hat{\omega}_M \\ \hat{\omega}_L \\ \theta_S \end{bmatrix} + \begin{bmatrix} K_{Tn} \\ J_{Ln} \\ 0 \end{bmatrix} \tau_L \]  

Here, the derivative of the load-side velocity is obtained directly using \( \dot{\omega}_L = a_L \), in the case when the load-side acceleration \( a_L \) is detected by using an acceleration sensor. The following equation is obtained for the estimation of the load torque using \( a_L \).

\[
\tau_L = K_{Sn} \theta_S = D_{Ln} \dot{\omega}_L - J_{Ln} a_L \]  

Equation (2) expresses that \( \tau_L \) is obtained instantaneously using \( a_L \). To compensate for the initial state error, this paper designs a state observer using an observable output \( \hat{\omega}_M \). The observer gain \( k \) is used to express the state observer of a two-inertia system. Finally, the state equation of an instantaneous state observer (ISOB) is expressed as follows.

\[
\frac{d}{dt} \begin{bmatrix} \hat{\omega}_M \\ \hat{\omega}_L \\ \theta_S \end{bmatrix} = \begin{bmatrix} \frac{D_{Mn}}{J_{Mn}} & 0 & -K_{Sn} \\ 0 & -k_2 & 0 \\ \frac{1}{R_{gn}} & -k_3 & 0 \end{bmatrix} \begin{bmatrix} \hat{\omega}_M \\ \hat{\omega}_L \\ \theta_S \end{bmatrix} + \begin{bmatrix} K_{Tn} \\ J_{Ln} \\ 0 \end{bmatrix} \tau_L \]  

\[
\hat{\tau}_L = \begin{bmatrix} 0 \\ -D_{Ln} \end{bmatrix} \begin{bmatrix} \hat{\omega}_M \\ \hat{\omega}_L \end{bmatrix} J_{Ln} a_L \]  

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The performance of an ISOB is affected with the load-side acceleration sensor. Hence, to reduce noise reduction of the compensation current. The torque estimation performed with the load-side acceleration sensor; this paper uses a variable noise-covariance (VNC) Kalman filter\(^5\). This filter uses the following variable noise-covariance matrix:

\[
R = \sigma \quad \text{when} \ (\sigma > R_S) \tag{5}
\]

\[
R = R_S \quad \text{when} \ (0 < \sigma \leq R_S) \tag{6}
\]

\[
\sigma = \left[ \frac{1}{N} \sum_{i=1}^{N} (a_{L_sense} - M)^2 \right]^{1/2}, \quad M = \frac{1}{N} \sum_{i=1}^{N} a_{L_sense} \tag{7}
\]

The Kalman filter obtains \(a_L\) using the following equations.

\[
P_k(k-1) = AP_{k-1}(k-1) + Q \tag{8}
\]

\[
K_k = P_{k(k-1)} + H^T \left( H P_{k(k-1)} H^T + R \right)^{-1} \tag{9}
\]

\[
a_{L(k)} = a_{L(k-1)} + K_k \left( \alpha_{L_sense(k)} - H a_{L(k-1)} \right) \tag{10}
\]

\[
P_{k(k)} = P_{k(k-1)} - K_k H P_{k(k-1)} \tag{11}
\]

A Kalman-filter-based ISOB (KFISOB) estimates the \(T_L\) on the basis of \(a_L\) calculated by the VNC Kalman filter.

### 3. Experiments

In this paper, the effectiveness of proposed method is confirmed by performing experiments using the upper arm of an industrial robot. Figure 1 shows the block diagram of the proposed motion control system. Table 1 shows the parameter list of the motion control system. The estimated load torque is input to the control system through a transfer function \(T_m(z)\). A low-pass filter (LPF) is used for the noise reduction of the compensation current.

\[
T_m(z) = \frac{I_{mp} \omega_L}{\omega_L T_L z^{-1}} = \frac{1}{z^{-1}} b_L z^{-3} + b_L z^{-2} + b_L + b_L \tag{12}
\]

Figure 2 shows the numerical simulation results. The robot arm starts to accelerate and decelerate at 0.1 [s] and 1.5 [s], respectively. The velocity response is balanced between the motor torque and the friction torque & the inertial torque. At 0.8 [s], the velocity decreases by inserting the step load compensation method involving the use of a KFISOB. The decrease in velocity caused by the insertion of the step load torque is reduced by using the KFISOB. The effectiveness of the proposed method is confirmed by performing both a numerical simulation and experiments using an industrial robot arm. The results of this paper show that the proposed method can be applied to achieve high-performance dynamic torque compensation of industrial robots.

### References
