Force-free control of low drag resistance for humanoid robot joint

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Abstract. A method for the force-free control of humanoid robot joints is presented that meets human–machine cooperation functions of a humanoid robot. To ensure accurate torque control, the current loop of the permanent magnet synchronous motor was initially optimised and its dynamic response improved with a compensating back electromotive force. The motor speed is then estimated by sampling the voltage and current, the values of which are used in the calculation of the joint angle and the gravitational-force compensation. Finally, a method to evaluate the dynamic force compensation is applied that then yields the motor output offset, the total gravitational load, the partial inertia force, and the partial friction moment. Experimental results show that this method reduces the drag torque to less than 1 Nm. This method can be widely applied to a variety of robotic joints.

1. Introduction

With the development of robotic technology, humanoid robots are playing a greater role in performing daily services, in numerous production industries, rescues in dangerous environments, and in other fields [1] [2] [3]. Human–machine interfacing is increasingly becoming widespread [4] [5]. In some application scenarios such as robot teaching [6] [7], the operator must guide the robot manipulator to a certain position or manipulate it into a specific pose. If the robot link is heavy or the joint is stiff, the operator may find the task difficult to complete. Moreover, ensuring the robot maintains the pose is important once the external force is removed [8] [9]. One common way to accomplish this task is to counterbalance the gravitational and inertial forces, as well as the friction exerted on the robot, so that the operator can smoothly manoeuvre the robot into any position. Force-free technology is designed to solve this problem.

At present, one mainstream method for force-free control is based on a six-dimensional force sensor mounted at the end of the robot [10] [11]. By decoupling the information of the sensor and transforming the force information into position, the robot can be manoeuvred in the direction of the external force. This control method is easily realized and the applying force is small. However, the operator can only apply the force at the end of the robot because its body is unable to sense the external force [12]. Unfortunately, the operator cannot change the angle of every joint.

To solve this problem another method, which is based on the joint current, was presented by Kushida [13]. With this method, the robot senses the external force by simply converting the current and moment. In this way, every joint can sense the external force. However, the current only changes when the joint starts to rotate, thereby creating a large initial drag moment.
To sense the external force precisely, Goto and colleagues presented a method based on sensing the joint torque [14]. This method provides the compensation to overcome friction and gravitational forces on the robot. Nonetheless, inertial forces are ignored, and the parameters of the dynamic model require precise evaluation.

Based on the above considerations, this paper presents a method for force-free control exploiting a combination of motor control optimization and feedback from torque sensors. By improving the dynamic response of the motor current loop and using the dynamic forces compensation, this method decreases the multiple drag resistances. The compensations overcoming the gravitational and inertial forces and friction use only the mass of the load. This force-free control of a single joint can be easily adapted to multiple joints as encountered with humanoid robots. In addition, the optimization of the motor control also assists in improving the performance of the robot.

2. Control of the permanent magnet synchronous motor (PMSM)

2.1. Mathematical model of the PMSM

To simplify the control of the PMSM, a mathematical model expressed in the synchronous rotating coordinate system is used in this study. Three assumptions are made:

(1) Magnetic saturation of the motor core is not considered;
(2) A symmetrical sinusoidal current is applied to the three-phase stator coil of the motor;
(3) Eddy currents and hysteresis losses are not considered.

The voltage model is as follows:

\[
\begin{align*}
    u_d &= R_i + L_d \frac{di_d}{dt} - \omega_e L_q i_q \\
    u_q &= R_i + L_q \frac{di_q}{dt} + \omega_e (L_d i_d + \phi_f)
\end{align*}
\]

where \( u_d \) and \( u_q \) denote the d and q-axis voltages, \( i_d \) and \( i_q \) the d and q-axis currents, \( L_d \) and \( L_q \) the d and q-axis inductances, \( \omega_e \) the angular speed of the electrical current, \( R \) the resistance of the stator, and \( \phi_f \) the flux of the permanent magnet.

The electromagnetic torque is calculated using

\[
    T_e = \frac{3}{2} p_n i_q (L_d i_d + \phi_f - L_q i_d)
\]

where \( p_n \) is the polar number of the motor.

For a surface-mounted permanent magnet motor, \( L_d = L_q = L \).

2.2. Back EMF compensation

After discretizing the mathematical model for the motor in the synchronous rotating coordinate system, an equation is obtained for the back EMF, which is represented by \( u_b \) [15],

\[
\begin{align*}
    u_{bd}^{n-1} &= u_d^{n-1} - R i_d^{n-1} - L_d \frac{i_d^n - i_d^{n-1}}{T} \\
    u_{bq}^{n-1} &= u_q^{n-1} - R i_q^{n-1} - L_q \frac{i_q^n - i_q^{n-1}}{T}
\end{align*}
\]

where T donates the sampling period, n and n-1 the number of sampling period.
In this way, the \( d \) and \( q \)-axis back EMF of the last moment can be calculated easily because only the inductance and resistance values are necessary. The voltage and current can be monitored in real time. The period for the control cycle of the motor is 50 \( \mu \)s. Over several successive cycles, the change in back EMF is very small. Therefore, the current back EMF can be estimated by averaging the back EMF in the last two control cycles. The current back EMF is expressed as

\[
\begin{align*}
\begin{cases}
u_{bd}^* = \frac{1}{2} \left[ u_d^{n-1} + u_d^{n-2} - R(i_d^{n-1} + i_d^{n-2}) - \frac{L_d}{T}(i_d^n - i_d^{n-2}) \right] \\
u_{bq}^* = \frac{1}{2} \left[ u_q^{n-1} + u_q^{n-2} - R(i_q^{n-1} + i_q^{n-2}) - \frac{L_q}{T}(i_q^n - i_q^{n-2}) \right]
\end{cases}
\]

(4)

In controlling the PMSM with back EMF compensation (figure 1), the current and voltage of the motor are sampled in real time. By a coordinate transformation, the current and voltage in the \( d \) and \( q \) synchronous reference frame can be obtained. After calculating the back EMF using equation (4), the evaluation of the compensation is completed.

2.3. Speed monitoring without encoder

Speed estimates can be used in calculating the joint angle without the need for an encoder. The joint angle is then used in the estimate of the compensation of the gravitational force.

From equation (1), we see that the speed information is contained in the back EMF. After the back EMFs \( u_{bd} \) and \( u_{bq} \) are obtained, we can calculate the angular speed of the electrical current from the expression

\[
\hat{\omega}_e = \frac{u_{bq}}{2(L_d i_d + \varphi_f)} - \frac{u_{bd}}{2L_q i_q},
\]

(5)

which, with the polar logarithm \( p \), yields the angular speed of the machine

\[
\hat{\omega} = \frac{\hat{\omega}_e}{p}
\]

(6)

where \( \hat{\omega} \) denotes the estimate of the motor speed; by taking averages, its error decreases. To verify the feasibility of this method, a simulation was conducted of the calculation of the speed. A comparison of the estimate and the actual value (figure 2) shows that the error of the estimate and its delay caused by the calculation delay of the back EMF are very small.
3. **Force-free control**

Assuming the flexibility of the torque sensor and the reducer are small, the connection between the motor output and the load is simplified as a spring. The model of the joint (see figure 3) yields the moment transfer equations, which are written

\[
\begin{cases}
\tau + \tau_{\text{out}} = M\ddot{q} + V(q, \dot{q}) + g(q) \\
\tau = K(\theta - q) \\
B\ddot{\theta} + \tau = \tau_{\text{in}} - \tau_f
\end{cases}
\]  

(7)

where \( B \) denotes the inertia of the motor rotor, \( K \) the stiffness coefficient of the equivalent spring, \( M \) the moment of inertia of the load, \( \tau_{\text{in}} \) the output moment of the motor (the moment that drives the motor rotor), \( \tau_f \) the moment of friction of the joint, \( \tau \) the driving moment of the joint under load (the value measured by the joint torque sensor), \( \theta \) and \( q \) the angles of the motor and the load end (both \( \theta \) and \( q \) are converted to one end of the reducer), \( V(q, \dot{q}) \) the centrifugal and Coriolis forces, and \( g(q) \) the real-time gravitational torque of the load. Depending on the distance \( r \) between the centre of mass of the load and the centre of the joint, and the load mass \( m \), \( g(q) \) is expressed as \( mgr \sin(q) \). Here, \( \dot{q} \) and \( \ddot{q} \) denote the first- and second-order derivatives of \( q \), and \( \ddot{\theta} \) the angular acceleration of the motor.
The motor is controlled to output a torque, \( \tau_m = \tau + K(g(q) - \tau) \). Substituting \( \tau_m \) into the moment transfer equations yields the dragging torque \( \tau_{out} \) of the operator [16],

\[
\tau_{out} = M\ddot{q} + V(q, \dot{q}) + \frac{1}{K} B\dot{\theta} + \frac{1}{K} \tau_f.
\]

(8)

If \( K > 1 \), both the inertia force \( B\dot{\theta} \) and friction torque \( \tau_f \) are effectively suppressed. Thus both torques are partially compensated and only a small external torque is needed to execute a smooth guide.

Viewing the total control block diagram (figure 4), we see the back EMF is compensated by discretization method to improve dynamic response. Furthermore, an estimate of the motor speed can be made and applied in the calculation of the dynamic force compensation. Finally, the gravitational force of the load, the friction moment, and the inertia force of the motor can be compensated, thereby completing the zero-force drag experiment.

Figure 4. Total control block diagram.

4. Experimental results

4.1. Setup of the experimental equipment

The experiment platform is equipped with a fixed robot joint (figure 5), a robot link with load, a joint driver, and a hysteresis brake. The joint driver (figure 6) handles the joint position, speed, acceleration, torque, and other information, and controls the current, position, and torque. The drive chip is a TMS320F28377D operating at a frequency of 200 MHz. The joint torque sensor SRI M2210D measures the torque in the direction of the joint axis. The sensor’s range is 300 Nm. The hysteresis brake provides a specified torque at any speed of the motor.

Figure 5. Robot joint.  Figure 6. Driver of the joint.
4.2. Motor control experiment

The dynamic response of the current loop is tested in a speed-step experiment. The reference speed is set to a step-form with a maximum speed of 1000 rpm. In comparing the current and speed curves (figures 7 and 8), the current fluctuation is seen to be smaller, and the speed transition time of the back EMF compensation control is shorter. The curves also show that dynamic performance of the current loop has improved. This improvement in performance ensures a smooth zero-force dragging of the joint, thereby outputting the expected torque faster.

Figure 7. Q-axis current: a) proportional–integral (PI) closed-loop control, b) Back EMF compensation control.

Figure 8. Curves associated with the angular speed: a) PI closed-loop control, b) Back EMF compensation control.
4.3. Zero-force drag experiment

In the experiment demonstrating zero-force dragging, the feedback value from the torque sensor was compensated first, and the stiffness coefficient $K$ was increased gradually; the larger $K$ is, the smaller the force needed to drag the joint. However, a large $K$ may cause chatter of the joint because of noise generated from feedback in the torque sensor. By using a second-order Butterworth filter, the torque signal is smoother and the guiding force is reduced further. The equation governing the filter output is

$$H(z) = \frac{b_1 + b_2 z^{-1} + b_3 z^{-2}}{1 + a_2 z^{-1} + a_3 z^{-2}},$$

(9)

where $a_2 = -1.9987$, $a_3 = 0.9987$, $b_1 = 2.1834 \times 10^{-7}$, $b_2 = 4.3667 \times 10^{-7}$, $b_3 = 2.1834 \times 10^{-7}$.

Two groups of experiments with different control methods were conducted. A simple gravity compensation is used as the method for the control group. When the joint is stationary and in a fixed position, a very small dragging force is applied to the joint that is not enough to make the joint turn. Then the dragging force is gradually increased until an angular displacement is obtained. Recording sampling data of the change in the joint torque sensor during this process yields the initial drag moment being the difference in readings. The torque curves are shown in figure 9; values of the initial drag moment are listed in table 1.

![Figure 9. Initiating the drag moment: a) Gravity compensation, b) Dynamic force compensation, c) Compensation with Butterworth filter](image)

| Control method                      | First group | Second group | Third group | Fourth group |
|-------------------------------------|-------------|--------------|-------------|--------------|
| Gravity compensation (Nm)           | 5.37        | 5.24         | 4.61        | 5.27         |
| Dynamic force compensation (Nm)     | 0.85        | 0.81         | 0.85        | 0.83         |
| Torque reduction ratio (%)           | 84.2%       | 84.5%        | 81.6%       | 84.3%        |

From the results of the experiment, one sees a simple gravitational compensation with dragging forces no larger than about 5.5 Nm. Dynamic force compensation requires smaller dragging forces of less than 1 Nm. The inertia force, gravity torque of the load, and the friction moment of the joint are compensated partially or entirely. An operator is able to drag the joint to any position using minimal force and can stop the joint in the required position without applying an external force.

5. Conclusion

A method for the force-free control of a humanoid joint was presented. The optimal control of the current loop compensates the back EMF of the PMSM, which shortens the transition time of the current. Precise speed estimations calculated from sample values of the voltage and current avoids the need for an encoder. A dynamic force compensation using only the load gravity parameter completes the estimation of a smooth zero-force drag, which circumvents the complex process of identifying the
dynamic parameter. Moreover, dynamic force compensation control reduces the maximum drag torque by about 85%. By applying this control method based on motor control optimization and torque-sensor feedback, the evaluation of the zero-force dragging for any humanoid robot joint is easily completed, and hence a wide range of applications is envisaged.

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