Torque and Speed Control of DC-Servomotors for Robots

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DC servomotors as applied to robots and machine tools can be applied either as torque control devices or speed control devices. For torque control the current to the motor is the input variable, and for speed control the voltage is the input variable. The selection of the appropriate type of control variable is based upon the operating systems and in each case a different control loop structure is required. The present paper is concerned with the design of the control loops and the selection of controller types. Guidelines are presented for choosing the appropriate type of control loop for robot systems.

Introduction

Most small to medium size robots utilize DC servomotor actuators. Two alternative approaches exist to the control of the motion of a robot arm driven by DC motors [1]. One approach is to control the torque of the robot arm by manipulating the motor current. Another approach is to control the motor rotational speed by manipulation of the motor voltage. The first approach, based on manipulation of current, treats the torque produced by the motor as an input to the robot joint as shown in Fig. 1. The second approach, based on manipulation of voltage, treats the robot arm as a load disturbance acting on the motor's shaft, as shown in Fig. 2. This basic distinction is not merely a philosophical one, and has important practical consequences for the final control system design.

A straight forward approach to the control of robot arm motion is to apply at each joint the necessary torque to move the manipulated object and to overcome friction, gravity forces, and dynamic torques due to the moment of inertia. Torque control, based on manipulation of DC motor current, utilizes usually a current amplifier in the motor's drive unit. A current amplifier is a device which supplies a current proportional to its input voltage, and has a high output resistance.

The alternative approach is to control the speed of the robot arm by manipulation of the DC motor voltage, utilizing a voltage amplifier in the motor's drive unit. Similar approach is also usually used in hydraulic driven robots. A voltage amplifier provides an output voltage proportional to its input voltage, and is capable to supply the current required by the motor.

The present paper compares the two approaches and provides recommendations to the adjustments of the gains in the two loops. The controller in all cases is a microprocessor, but the analysis neglects the effect of sampling in the control loop. This is allowed since the sampling period is much smaller than the dominant time constant of the control loop.

Control Loop Using Current Amplifier

One approach to the control of robot joint motions is to apply an appropriate torque to overcome gravity, friction, and dynamic torques due to the moment of inertia, J. Several such control loops are discussed in the literature [2-8], and a relatively sophisticated loop with a compensation for the moment of inertia and gravity torque is discussed in this paper.

The block diagram of the compensated torque control loop is shown in Fig. 3. It contains a proportional-derivative (PD) controller, where the proportional gain K_p causes a finite steady-state error (for a step input) and the derivative gain K_d must be added from stability considerations. Compared with basic control loops, the compensated loop in Fig. 3 contains the following features:

1. An estimation of the moment of inertia $\hat{J}$ is inserted as a programmed gain. The gain $\hat{J}$ can be introduced either as in Fig. 3 [7] or in the acceleration feedforward block alone, i.e., $\hat{J}s^2$ [6].
2. An estimation of the static torque due to gravity $\hat{T}_g$ is programmed in order to reduce (or eliminate) the relevant steady-state error.
3. An acceleration feedforward term is added in order to improve the accuracy in obtaining the required dynamic torque.

The equations of the compensated loop are as follows:

$$T = \{[(\theta_r-\theta)(K_d s+K_p) + s^2\theta_r]\hat{J} + \frac{\hat{T}_g}{s}\}K_a K_t \qquad (1)$$

$$\text{and} \quad \theta = (T - T_s)/Js^2 \qquad (2)$$

Combining Eqs. (1) and (2) yields the closed-loop equation:

$$\theta = \frac{\hat{J}(K_a K_t s^2+K_1 s+K_2)\theta_r - T_s + K_a K_t \hat{T}_g/s}{Js^2 + \hat{J}K_1 s + \hat{J}K_2} \qquad (3)$$

where

$$K_1 = K_a K_t K_d \text{ and } K_2 = K_a K_t K_p .$$

Equation (3) represents a second order system with a damping factor of

$$\zeta = \frac{K_1}{2}\sqrt{\frac{\hat{J}}{K_2 J}} \qquad (4)$$

and a natural frequency of

$$\omega_n = \sqrt{\frac{\hat{J}K_2}{J}} \qquad (5)$$

In this system the amplifier gain is adjusted such that

$$K_a K_t = 1 \qquad (6)$$

Consequently, Eq. (3) becomes

$$\theta = \frac{(s^2+K_1 s+K_2)\theta_r - (T_s-\hat{T}_g/s)/\hat{J}}{(J/\hat{J})s^2 + K_1 s + K_2} \qquad (7)$$

and the steady-state position error for a step input is

$$E = \theta_r - \theta = \frac{T_s - \hat{T}_g/s}{\hat{J}K_2} \qquad (8)$$

where T_s is the Laplace transform of a torque which at the steady state is a constant T_g caused by the gravity force, namely

$$T_s = \frac{T_g}{s} \qquad (9)$$

If the estimated torque $\hat{T}_g$ is equal to the actual torque T_g, the steady-state position error is zero.

Similarly, if the estimated inertia $\hat{J}$ is equal to the actual inertia, J, Eq. (7) yields the ideal situation $\theta=\theta_r$ and consequently, from Eq. (2)

$$T = Js^2\theta_r + \frac{T_g}{s} \qquad (10)$$

so that the motor always produces the required dynamic and static torques.

The obvious problem with this type of system is the need to have an accurate estimate of the changing gravity torque and moment of inertia in order to obtain the desired position and dynamic response. If the moment of inertia is well estimated, then $J = \hat{J}$ and the ideal response $\theta(t) = \theta_r$ is obtained regardless of ζ. If, however, $\hat{J} \neq J$, catastrophic results might occur. This is demonstrated in Fig. 4. Assume that the gain $\hat{J}$ was adjusted so that $\zeta = 0.71$ for $\hat{J} = J_{av}$ and consequently the corresponding response is an ideal step. If the actual J becomes 8 times larger, then the damping factor is reduced to $0.71/\sqrt{8} = 0.25$, which results in an overshoot of 46%. A similar phenomenon occurs also with the basic loop. However, if the actual J becomes 8 times smaller than $\hat{J}$, then $\theta(0) = 8\theta_d$ and the corresponding overshoot is 700%! This must be avoided by all means.

The compensated loop can operate either with a variable gain, where $\hat{J}$ varies during the arm motion, or with a fixed gain J. If $\hat{J}$ is a fixed gain, the best performance is obtained by adjusting it to $\hat{J} = J_{min}$. This guarantees that $\hat{J}/J < 1$. When the actual inertia is at its minimum, the maximum damping factor is achieved, as can be seen from Eq. (4). The minimum damping factor occurs at J_{max}, so to avoid large overshoots it is desirable to adjust the gains such that $\zeta_{min} > 1$. This Min-Max adjustment method produces

$$\zeta_{min} = \frac{K_1}{2}\sqrt{\frac{J_{min}}{K_2 J_{max}}} > 1$$

and

$$\zeta = \zeta_{min}\sqrt{\frac{J_{max}}{J}}$$

Figure 5 demonstrates responses obtained by this method, when variations of 10:1 are expected in the effective inertia. (This range of variations is used in [9]).The minimum damping factor is adjusted to $\zeta = 1.05$, and results in a maximum overshoot of 11%. For a smaller inertia the overshoot is smaller as well. For $J = J_{min} = 0.1\,J_{max}$ the response is an ideal step. However, if for any reason $J<J_{min}$ an overshoot occurs at t = 0, as is shown by the dashed line in Fig. 5.

The compensated loop might provide a satisfactory solution for variable-gain loops, in which the value of $\hat{J}$ is continuously adjusted by the robot computer. In practice, however, commercial robots operate with fixed gain loops, and in these cases the compensated loop has the following drawbacks:

1. There always exists an overshoot to a step response. This situation can be remedied if a tachometer feedback is added to the control loop. In this case, however, the loop is no longer a torque control loop.

2. The double derivative (s^2) does not actually function when step and ramp inputs are provided. The above analysis assumed linear model, and consequently the response of a derivative to a step or a double derivative to a ramp input is an infinite impulse. But the allowable current to the motor is limited. This means that during the initial starting period the response of the motor is

$$\theta = \frac{K_t I_m t^2}{2J} \qquad (11)$$

regardless of the value of $\hat{J}$ or θ_d. This response continues until the current is reduced below the I_m value by the feedback. Later on the input is constant (for a step) and the double derivative has no effect. Thus the compensated loop behaves for step or ramp inputs similarly to the basic loop.

3. Errors due to approximations in modeling (e.g., $T = J\ddot{\theta} + T_s$) and system nonlinearities prevent the ideal response even for $J \approx \hat{J}$.

4. Gravity torques must be computed in real time in order to be compensated. This requires a large program and a lengthy computing time [6].

Control Loop Using Voltage Amplifier

An alternative approach is to control the speed of the robot joint by manipulation of the motor voltage utilizing a voltage amplifier [10-12] as shown in Fig. 2. A block diagram of a basic control loop is shown in Fig. 6. The output of the loop is defined as either the speed or the position of the robot joint. The torque T_s is mainly due to coupling inertia and gravity acts as a disturbance on the motor.

The control loop in Fig. 6 includes an inner loop consisting of the voltage amplifier with a gain K_a, the DC motor and a tachometer as a velocity feedback device with a gain K_f. The transfer function of the inner loop is derived as follows.

The input voltage to the motor is

$$V(s) = K_a[V_u(s) - K_f\omega(s)] \qquad (12)$$

Combining the motor's speed equation,

$$\omega(s) = [K_m V - (RK_m/K_t)T_s]/(1 + s\tau)$$

with Eq. (12) yields:

$$\omega(s) = \frac{\alpha K_a K_m V_u(s) - (RK_m/K_t)\alpha T_s(s)}{1 + s\alpha\tau} \qquad (13)$$

where we have defined an attenuation factor

$$\alpha = \frac{1}{1 + K_a K_f K_m} \qquad (14)$$

The effect of the tachometer feedback is to reduce the time constant (since $\alpha<1$, then $\alpha\tau<\tau$), to reduce the effect of the load torque, to reduce any nonlinearities of the voltage amplifier, and to facilitate the adjustment of the overall gain by adjusting the gain K_f.

Comparing the loop structure in Fig. 3 and Fig. 6 shows that the derivative controller is no longer necessary and a proportional controller, with a gain K_c, is sufficient. The corresponding equation is

$$\theta(s) = \frac{K\theta_r(s) - K_q T_s(s)}{\tau' s^2 + s + K} \qquad (15)$$

where K is the open-loop gain defined by

$$K = \alpha K_a K_m K_c \qquad (16)$$

K_q is a gain defined by

$$K_q = \frac{\alpha R K_m}{K_t}$$

and

$$\tau' = \alpha\tau = \frac{\alpha R J}{K_t K_v} \qquad (17)$$

The characteristic equation of the closed loop is of the second order where the damping factor is

$$\zeta = \frac{1}{2\sqrt{K\tau'}} \qquad (18)$$

and the natural frequency is

$$\omega_n = \sqrt{\frac{K}{\tau'}} \qquad (19)$$

The actual position response to a position step input (for $T_s=0$) in a critically damped system ($\zeta = 1$) is shown in Fig. 7. Note that in this case the overshoot is zero, compared with 11% in Fig. 5. The problem is, however, that since τ' is proportional to the inertia J, the present loop also has the unfavorable situation of a damping factor which depends on a changing moment of inertia. In addition, this loop has not remedied the problem of the existence of a torque dependent position error at the steady state.

Elimination of Stationary Position Errors

The steady-state position error of the control loop shown in Fig. 6 is

$$E = \frac{K_q T_g}{K} \qquad (20)$$

Namely a position error due to gravity forces exists at the end-point. The explanation of this error can be found by substituting the values K_q and K from Eq. (16) into (20) which yields

$$EK_a K_c = \frac{R}{K_t}\,T_g \qquad (21)$$

Equation (21) means that when the joint is stationary the voltage amplifier supplies a voltage $V = EK_aK_c$ to counteract the effect of the gravity torque T_g. To generate this voltage a position error E must exist and consequently the joint does not reach the required end-point position. In the current-amplifier loop this situation was remedied by programming an estimated gravity torque to counteract the real one. Obviously, the same approach can be also applied here. However, since the real gravity torque depends upon the angle values of the various joints, it is difficult to have an accurate estimate of the torque values for every position of the manipulator, and therefore this method has only low practical usefulness.

An alternative approach to eliminate the stationary (i.e., the steady-state) position error is to add an integral or a proportional-integral (PI) controller into the internal loop of Fig. 6. The input to an integrator at steady state must be zero, and therefore with this loop $\omega = V_u = 0$. Since V_u is zero, the steady-state position error E is zero as well, and the joint reaches the desired end position. The output of the PI controller generates the voltage V required to overcome the effect of gravity at steady state.

The proposed control loop requires a careful design since the characteristic equation is of the third order rather than second order as in the previous loop (see Eq. 15), and inappropriate selection of the loop gains will cause an unstable system. An improved stability is obtained by using the PI controller in the internal loop, rather than an integral alone. The PI-controller guarantees zero position error when the joint is in no-motion together with an unoscillatory response during the motion itself.

Conclusions

Two alternative methods to the control of robot arms have been proposed: Torque control utilizing a current amplifier and speed control utilizing a voltage amplifier. The main problem with the torque control system is the need to have an accurate estimate of the moment of inertia at each joint of the robot arm in order to obtain the desired trajectory. If the actual value of the inertia is smaller than expected, then the torque applied is larger than required. This torque is translated to higher acceleration and consequently higher velocity. This can have disastrous consequences, for example, a part can be struck and broken since the velocity is not zero as desired at the target position. In order to avoid this situation, a Min-Max adjustment policy has been proposed in the paper.

An important advantage of the torque control approach is that we can maintain a desired torque or force. This is useful in some robotics applications, such as screwing or assembly of mating parts. Another advantage is that when the robot arm enounters resistance (e.g., the gripper touches a rigid obstacle) it maintains a constant torque, and does not try to draw additional power from the electrical source.

The alternative method provides speed control of the robot joints. The main advantage of this approach is that variations in the moment of inertia effects only the time constant of the response but do not result in any disastrous consequences, and does not affect the time required to reach the target position. The arm always approaches the target smoothly with a very small speed. The problem with this approach is that the torque is not controlled, and the motor will draw from the voltage amplifier whatever current is required to overcome the disturbance torque. This can lead to burning of the amplifier's fuse, when the robot arm encounters a rigid obstacle. Another disadvantage is that this system is not suitable for certain assembly tasks, such as press fitting and screwing, which require a constant torque or force.

The selected control approach should be dependent on the application and the environment in which the robot arm operates. When the arm is free to move along some coordinate (e.g., spray painting robots), the specification of velocity is appropriate. When the robot's end-effector might be in contact with another object in such a way as to prevent motion along a coordinate, then the specification of torque is appropriate. Note that either velocity or torque may be specified, but not both.

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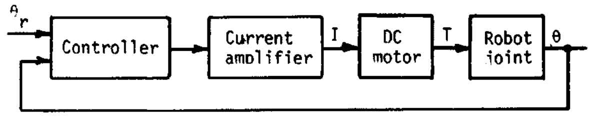

Fig. 1: Torque control of robot arm

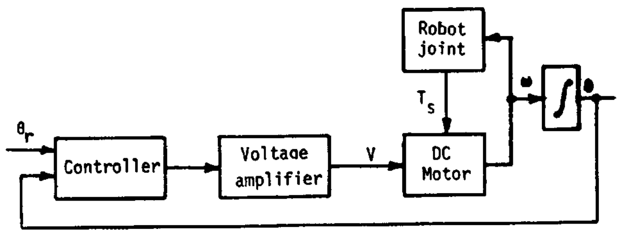

Fig. 2: Speed control of robot arm

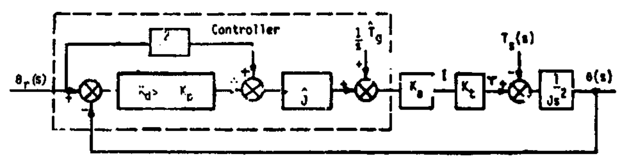

Fig. 3: Compensated torque control loop

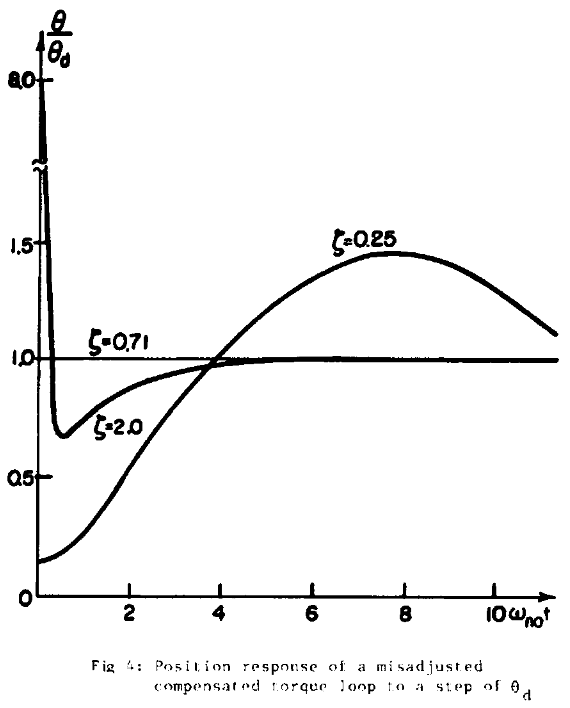

Fig 4: Position response of a misadjusted compensated torque loop to a step of θ_d

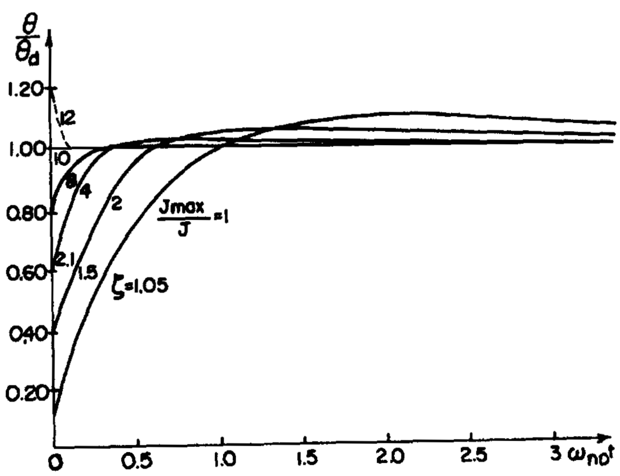

Fig. 5: Position response in a compensated loop adjusted according to the Min-Max method

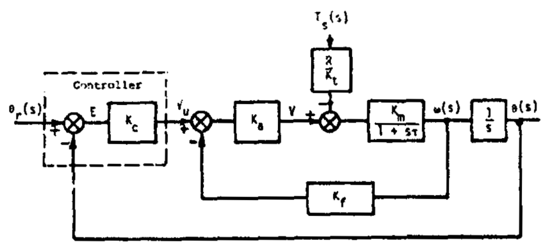

Fig. 6: Control loop using voltage amplifier

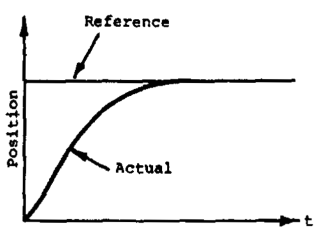

Fig. 7: Required and actual position response in a speed control loop