PARAMETER ESTIMATION OF A SINGLE-LINK ROBOTIC MANIPULATOR IN PRESENCE OF DEAD-BAND AND DEAD-ZONE

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ABSTRACT

An algorithm is presented for parameter estimation of a single-link robotic manipulator when there is dead-band between the duty-cycle of applied and actual PWM for the actuator and dead-zone (caused by backlash) in the torque transmission from actuator to the link. The proposed algorithm has two stages, in the first stage dead-band and one of the two system parameters is estimated using steady-state response and in the second stage, transient response of the manipulator motion profile not affected by dead-zone is used for the estimation of remaining parameter Precise curve fitting of the analytical model using estimated parameters to the manipulator position profile warrants the proposed technique.

KEY WORDS

Parameter estimation, Robotics, Dead-band, Dead-zone

1. Introduction

Optimal performance of any electrical, mechanical and electro-mechanical system can be attained using sophisticated control algorithms which are based on precise knowledge of system parameters. Typically system parameters are not known and have to be estimated. The same holds true for robotics, for example, a typical tracking controller for robotic manipulators is designed using feedback linearization [1] which is based on system parameters. Modeling perturbation severely degrades the performance of this controller and only ultimate boundedness instead of asymptotic convergence of the system trajectories is guaranteed. Complexity of system identification increases manifold in presence of nonlinear dynamics In case of robotic manipulators, dead-zone and dead-band pose major challenge in parameter estimation. Dead-band is the difference between the applied and actual duty-cycle of PWM for the actuator caused by aging and other inaccuracies in the drive circuits.

Dead-zone is caused by Backlash between the teeth of mating gears, this cause nonlinear torque transmission form actuator to the link resulting in position uncertainty, discontinuity and impact whenever torque reversal takes place. In this paper we have extended our work from our past contribution [16] in which parameter estimation of a single-link robotic manipulator was done in presence of backlash only. In this paper we have considered the presence of dead-band as well.

In the past, many researchers have explored parameter estimation of robotic manipulators. Least squares estimation technique has been used for parameter estimation of robotic manipulators assuming knowledge of geometric parameters in [10], [11], [12], [13]. Nonlinear dynamics of a single-link robotic manipulator have been estimated by Berhe and Unbehauen [14] using weighted least squares algorithm in the frequency domain for a manipulator with flexible joint. A general approach for system identification in presence of nonlinearities considering system model a linear map of unknown parameters has been proposed by Sun, Liu and Sano [15], their work primarily identifies memory-less nonlinearities but consider backlash as a special case.

The paper is organized as follows. Section 2 presents the mathematical model of a single-link robotic manipulator for motion in the horizontal plane and highlights the presence of dead-band and dead-zone in the model. Section 3 presents the manipulator hardware details that was used for the experimentation purposes. Section 4 presents the two stage parameter estimation approach Results are presented in Section 5 and these are followed by Conclusions and References.

2. System Model

The dynamical model of a single-link robotic manipulator [16] is given by

$$\dot{\omega} + b\omega = c\tau \, , \qquad (1)$$

Where ω and $\dot{\omega}$ are angular velocity and angular acceleration of the link respectively, $b = \frac{k}{m}$, where k is the coefficient of friction and m is the total mass of the link, and $c = \frac{1}{ml^2}$ where l is the centre of gravity of the link. Parameters b and c are unknown and have to be estimated.

We have considered that the torque is applied to the link by an electric motor. In this case the model of the manipulator from applied PWM to the angular velocity of the manipulator is represented by the following equation **[4]**

$$\dot{\omega} + b\omega = cV \ , \qquad (2)$$

where V is the duty-cycle of applied PWM.

2.1 Dead-band Nonlinearity

From the perspective of system identification, precise knowledge of applied input (PWM in our case) is of paramount importance. At the motor drive stage, aging and other inaccuracies in the power transistors result in a difference between the applied PWM and the actual PWM driving the actuator, this difference is termed as dead-band which can be mathematically incorporated in equation (2) as

$$\frac{1}{c}\dot{\omega} + q\omega = V + \delta \qquad (3)$$

where $q = \frac{b}{c}$ and δ is the dead-band In this paper we will estimate the parameters of the system in presence of this dead-band

2.2. Dead-zone Nonlinearity

Dead-zone nonlinearity is present as Backlash at the torque transmission stage. The presence of backlash modifies the dynamical model of the manipulator [8], [16] and equation (1) transforms into

$$\dot{\omega} + b\omega = c(\tau'(t))) \ , \qquad (4)$$

In equation (4), τ' is the output torque of the gear train, and is mathematically defined in terms of the output torque of the motor τ as

$$\tau'(t) = \begin{cases} m(\tau(t) - c_l & for\ \tau(t) < \tau_l \\ m(\tau(t) - c_r & for\ \tau(t) < \tau_r \\ \tau(t-1) & for\ \tau_l < \tau(t) < \tau_r \end{cases} \qquad (5)$$

Characteristics of τ' i.e c_l, c_r, τ_l, τ_r and $\tau(t-1)$ in equation (5), are presented in Figure 1.

In Figure 1, *m*>0 is the slope of the two parallel lines, c_l and c_r are the τ axis intersection points of the left and right hand side parallel lines respectively, τ_l and τ_r are the τ axis values of the intersection of the two parallel lines with the horizontal inner segment containing $\tau(t-1)$.

Considering the backlash model (5), it can be observed that for $|\tau| > \max[\tau_l, \tau_r]$, the manipulator can be driven outside the dead-zone region which implies proper meshing of driving and driven gears and thus linear torque transmission takes place.

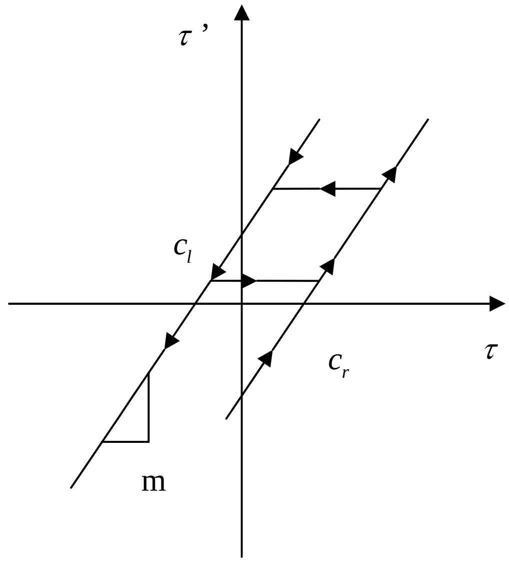

Figure 1 Backlash characteristics

In our previous work [16] we have shown that the region of linear torque transmission can be identified and used for parameter estimation i.e the dead-zone nonlinearity can be avoided.

3. Experimental Setup

For experimentation purpose, we developed a single-link robotic manipulator. The gear train designed for torque transmission has pronounced backlash at each gear stage, moreover the gear train is constructed from plastic gears this further enhances the effect of backlash

The overall reduction ratio of two gear stages is 14:84. A lumped mass at the end of the link is attached; this resembles a typical case of an end-effector carrying a load. The feedback of position of the manipulator is acquired using a 2500 pulses per revolution (PPR) quadrature shaft encoder. The shaft encoder is attached with the shaft of the final gear; this shaft contains the information of accumulated backlash at each gear stage. The position of the shaft is sampled at 2ms.

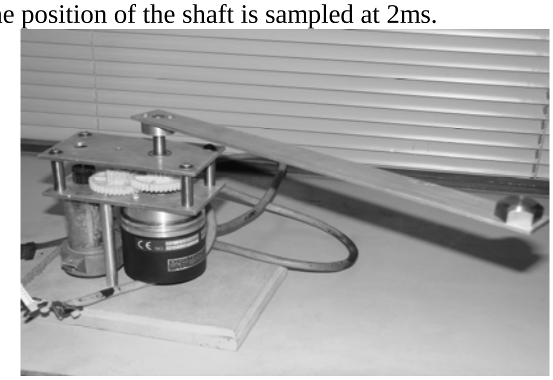

Figure 2 Experimental Setup

4. Estimation Approach

The parameter estimation approach presented in this paper has two stages. In the first stage, dead-band and the parameter q is estimated, in the second stage, the parameter b is estimated

4.1 Estimation of dead-band and parameter q

The dead-band and parameter q are estimated when the manipulator is in steady state, i.e when the angular velocity becomes constant and transient angular acceleration settle to zero. In steady state, the dynamical equation (3) becomes

$$q\omega_{ss} = V + \delta \quad (6)$$

The dead-band and parameter q are estimated by driving the manipulator into steady state region for different values of duty-cycle of applied PWM. In our case we had driven the manipulator for the following applied duty-cycles

$$V = [25, -25, 35, -35]^T \quad (7)$$

The unknown dead-bands corresponding to each applied duty-cycle are defined in the following vector

$$\Delta = [\delta_1, \delta_2, \delta_3, \delta_4]^T \quad (8)$$

The difference between the dead-band for the same magnitude forward and reverse applied PWM is constant and is termed as bias, mathematically

$$\delta_1 - \delta_2 = \delta_3 - \delta_4 = bias \quad (9)$$

The constant angular velocity vector

$$\Omega_{ss} = [\omega_{1ss}, \omega_{2ss}, \omega_{3ss}, \omega_{4ss}]^T, \quad (10)$$

corresponding to each applied duty-cycle of PWM in (7) is measured using quadrature shaft encoder.
The set of equations (6)-(10) has six equations and six unknown parameters, the solution of these equation gives the estimates of dead-band and the unknown parameter q.
The matrix form of the solution is given by

$$\begin{bmatrix} q \\ \delta_1 \\ \delta_2 \\ \delta_3 \\ \delta_4 \\ bias \end{bmatrix} = \begin{bmatrix} \omega_{1ss} & 1 & 0 & 0 & 0 & 0 \\ \omega_{2ss} & 0 & 1 & 0 & 0 & 0 \\ \omega_{3ss} & 0 & 0 & 1 & 0 & 0 \\ \omega_{4ss} & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & -1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 1 & -1 & -1 \end{bmatrix}^{-1} \begin{bmatrix} 25 \\ -25 \\ 35 \\ -35 \\ 0 \\ 0 \end{bmatrix} \quad (11)$$

Solution of equation (11) provides estimate of parameter q, dead-bands and the bias term.

4.2 Estimation of parameter b

The parameter b is estimated from the transient response of the manipulator, square wave voltage is applied to the motor and response of the system is observed, this is the conventional approach of system identification [5]. The frequency of the square wave is adjusted so that it is neither too low for the system to enter steady state, nor it is too high so that the system could not get out of the dead-zone nonlinearity region [16]. The response of the system is observed from the shaft encoder. In our previous work [16] we have shown that there are certain segments in the motion profile of the manipulator which are affected by backlash nonlinearity. The estimation approach is to use backlash free segments of the motion profile and estimate the system parameters by the method of nonlinear least squares estimation. We present a snapshot of motion profile in the following figure and indicate segments of motion profile affected by backlash and subsequently discarded.

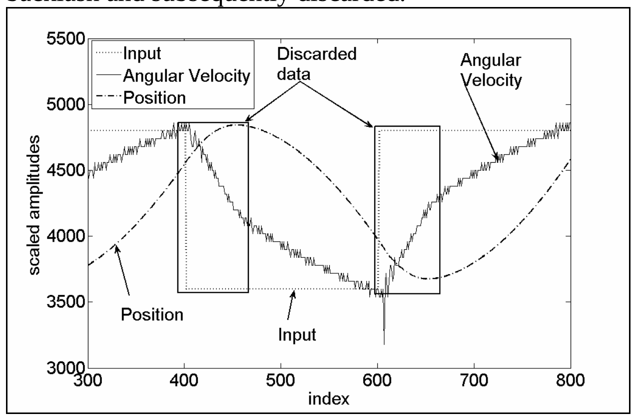

Figure 3 Discarded Data Segments

Data segment not affected by backlash are mathematically modeled from PWM to angular velocity by modifying equation (2) and introducing dead-band by the following equation

$$\dot{\omega} + b\omega = c(V + \delta) \quad (12)$$

Equation (12) is a linear first order ordinary differential equation [2] which has the solution

$$\omega(t) = \frac{1}{\hat{q}}(V+\delta) - \frac{1}{\hat{q}}(V+\delta)e^{-bt} + w(0)e^{-bt}. \quad (13)$$

The discrete time counterpart of (13) is

$$\omega[n] = \frac{1}{q}(V+\delta) - \frac{1}{q}(V+\delta)e^{-bnT} + \omega(0)e^{-bnT}, (14)$$

where $n = 0,1,2.............................N-1$. N is the total number of observations in the segment of data considered for estimation and T is the sampling time. Since $\hat{q}, V$ and $\hat{\delta}$ are known, equation (14) can be written as

$$s[n] = -\frac{1}{\hat{q}}(V+\hat{\delta})e^{-bnT} + \omega(0)e^{-bnT}, \quad (15)$$

where $s[n] = \omega[n] - \frac{1}{\hat{q}}(V+\hat{\delta})$.

Equation (14) has two unknown parameters b and the initial condition $\omega(0)$. The initial condition of the angular velocity has to be estimated because of the fact that some of the system data is discarded and only backlash free data segments are considered, then for every selected segment; the initial condition of angular velocity is unknown. Thus initial condition of angular velocity is an additional parameter that has to be estimated.

To estimate the parameters of equation(15), method of nonlinear least squares estimation **[6]** is used. This type of estimation is carried out when the system model is a nonlinear function of the unknown parameters, equation (15) can be written as

$$s[n] = A_1 r^n \tag{16}$$

Where

$$A_1 = \frac{1}{\hat{q}}(V + \hat{\delta}) + \omega(0) \quad r = e^{-bT} \tag{17}$$

It can be seen from equation (17), that the system model equation is linear in terms of parameters A_1 and nonlinear in terms of parameter r. The unknown parameters can be estimated using the method of nonlinear least squares estimation by separation of variables [6].

$$s = H(\alpha)\beta \tag{18}$$

in our case

$$\alpha = r \quad \beta = A_1 . \tag{19}$$

Considering the fact that the number of backlash free sample points selected from a single forward or reverse motion is 140

$$H(r) = \begin{bmatrix} r^0 \\ r^1 \\ r^2 \\ . \\ . \\ . \\ r^{139} \end{bmatrix} \tag{20}$$

The estimate of r is obtained by

$$\hat{r} = \max[x^T H(r)(H^T(r)H(r))^{-1} H^T(r)x] , \tag{4.16}$$

where x is the observation vector of the velocity of the manipulator. Maximization is done using the method of steepest ascent [3]

Once the value of r has been estimated, the estimates of A_1 can be obtained from

$$\hat{\beta} = \hat{A}_1 = (H^T(\hat{r})H(\hat{r}))^{-1} H^T(\hat{r})x . \tag{21}$$

5. Results

Parameters are estimated for each backlash free segment of the motion profile. These estimates are then used in the angular position equation of the single-link robotic manipulator. The plot of these equations is compared with the manipulator position data plot in Figure 4. From the figure it can be seen that very precise curve fitting using estimated parameters is obtained. This validates the suggested estimation procedure.

The average value of estimated parameters for 10 segments of motion profile not affected by backlash is as follows

b=0.52, c=0.0018**.**

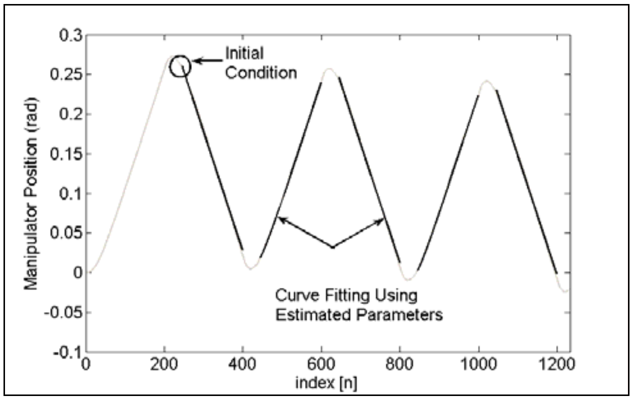

Figure 4 Curve fitting using estimated parameters

6. Conclusion

In this paper we have presented an algorithm for parameter estimation of a single-link robotic manipulator in presence of dead-band and dead-zone nonlinearities A two-step estimation approach is presented, in the first step dead-band and the ratio of the two system parameters is estimated from the steady-state response of the manipulator. In the second stage, the remaining parameters are estimated from the transient response of the system, the system data used for parameter estimation is carefully selected so that it is free from the effects of dead-zone nonlinearity caused by backlash in the gear train. In this stage parameter estimation is carried out using the method of nonlinear least squares. The results obtained for the proposed technique yield very accurate curve fitting to the manipulator position plot, which indicates precision of estimated parameters.

7. References

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