DEVELOPMENT OF HIGH PERFORMANCE SERVO DRIVE/ANTI DRIVE MECHANISM FOR BACKLASH REMOVAL

I. Askari, S. A Hassan, M. Altaf, A. Azim, M. B. Malik, K. Munawar

College of Electrical and Mechanical Engineering. Rawalpindi. Pakistan

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Abstract: In electromechanical drives, there is always a backlash between any pair of gears. Because of this, it is almost impossible to realize a high accuracy and high performance drive. However such drives are crucial in today's modern electromechanical systems. A high performance drive/anti-drive servo mechanism is developed to eliminate the effect of backlash. The concept utilizes redundant unidirectional drives to assure positive coupling of gear meshes at all times. Based on this concept, a methodology for enumeration of admissible redundant-drive backlash free mechanism has been established. The angular displacement is achieved as a difference of two torques. These torques can be controlled by a high performance control system. A controller model will be designed to move a single degree of freedom platform up to a desired span with a payload.

1 INTRODUCTION

Manipulators use gear trains for power transmission to allow actuators to be located in some desirable position. Gear trains are also used for torque amplification. Backlash is provided for prevention of jamming of gear teeth due to manufacturing errors or thermal expansion. However, backlash can cause momentary loss of coupling between two matting gears whenever there is torque reversal. It can result in motion discontinuity, position uncertainty, and impact in mechanical systems, which, in turn, make accurate control of manipulator difficult. End-effecter positioning accuracy is also compromise due to backlash. Precision gears, spring-loaded split gear assemblies, and precise mechanical adjustment are often used to overcome these difficulties. However, these techniques do not completely eliminate the backlash and can increase the cost of manufacturing and assembling.

Many methods such as backlash compensation (Veitschegger and Wu, 1986), antibacklash gears (Michalec, 1986), adjustable tooth thickness gears (Michalec, 1986), adjustable center distance (Dagalakis and Mayers, 1985) and harmonic drives (Calson, 1985) have been proposed for the elimination of backlash. Improvement on problems caused from gear backlash has been made by using these methods, e.g., backlash compensation used in machine tools. However, these methods become inadequate for robotic systems.

Presently none of these methods can eliminate backlash in robotics completely. For example, the method of adjustable center distance has been used for the assembly of PUMA 560 robot. The backlash control mechanism supplied by the manufacturer for the PUMA robot is an eccentric cartridge-bearing arrangement, as shown in figure1. Adjustable centers are subject to maladjustments, and in the field there is no assurance that the quality of a readjustment will be comparable to the original.

This paper is a continuation of our previous work where we developed a 2 DOF platform (Tanveer and Masood et al, 2005), designed the controller (Askari and Hassan et al, 2005), and finally modeled the system (Hassan and Askari et al, 2005). Besides the appropriate position as well as tracking control, the only flaw of that system was backlash that resulted in reduced efficiency for the tracking purposes. In this paper a new concept of drive antidrive mechanism has been described for one degree of motion which results in a minimum backlash between the gears to obtain a stable backlash free system.

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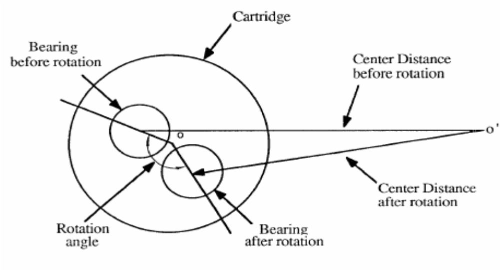

Figure 1: Backlash control mechanism using adjustable centre distance.

2 THE CONCEPT

Figure 2 shows a simple one-DOF gear train with two unidirectional drives, where D1 and D2 are the driving gears and F is the follower. The backlash in this mechanism can be controlled by applying torques to D1 in clockwise sense and D2 in a counter-clockwise sense at all times. The resultant torque acting on F will be in the counter clockwise or clockwise sense depending whether torque contributed by D1 is greater or less than that contributed by D2. Since no torque reversal is required to drive F, the effects of gear backlash are completely eliminated.

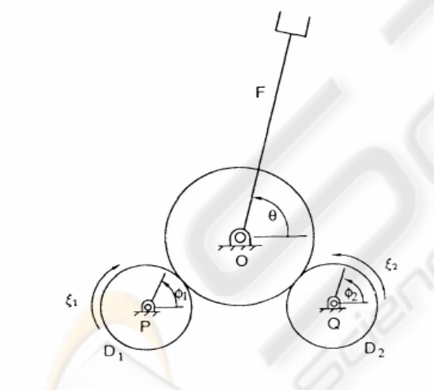

Figure 2: One-DOF Mechanism with redundant unidirectional drives.

The controllability can be analyzed from kinematics and static point of view. The kinematics equation for the mechanism shown in figure 2 can be written as:

$$\begin{bmatrix} \phi_1 \\ \phi_2 \end{bmatrix} = \begin{bmatrix} -\left(N_f / N_1\right) \\ -\left(N_f / N_2\right) \end{bmatrix} \theta \tag{1}$$

Where ϕ_1 and ϕ_2 and θ denote the angular displacements of gears D1, D2 and F respectively, and, N_1, N_2 and N_f represent their tooth numbers. Note that the negative sign stands for an external gear mesh.

For such a mechanical system, it can be shown that the input and output torques are related by following equation:

$$\tau_f = \left[-\left(N_f / N_1\right) - \left(N_f / N_2\right) \right] \begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} \tag{2}$$

Where ξ_1 and ξ_2 are the torques applied to D1 and D2 respectively, and, τ_f is the output torque on the follower F. Thus, given the input torques ξ_1 and ξ_2, the resultant joint torque, τ_f is uniquely determined. However, for a desired output torque τ_f, the required input torques are indeterminate. For example, the input torques can be expressed as:

$$\begin{bmatrix} \xi_1 \\ \xi_2 \end{bmatrix} = \begin{bmatrix} \dfrac{-N_1 N_2^2}{N_f \left(N_1^2 + N_2^2\right)} \\ \dfrac{-N_1^2 N_2}{N_f \left(N_1^2 + N_2^2\right)} \end{bmatrix} \tau_f + \lambda \begin{bmatrix} N_1 \\ -N_2 \end{bmatrix} \tag{3}$$

Where λ is an arbitrary real number. The first term on the right hand-side of (3) is referred to as the particular solution and second term the homogeneous solution. From (3) it is clear that by selecting proper positive λ, the sense of input torques $[\xi_1 \xi_2]^T$ can be maintained in the $[+-]^T$ direction at all times regardless of the value of τ_f. Similarly, the sense of input torques can also be maintained in the $[-+]^T$ direction by selecting a proper negative λ. Hence, the mechanism can be controlled by two unidirectional drives designed either in the $[+-]^T$ direction or in the $[-+]^T$ direction. Since the input torques can be maintained in the predetermined unidirectional senses at all times, backlash will never occur.

3 MANIPULATOR CONSTRUCTION AND DYNAMIC MODEL

3.1 Construction

A high performance drive/anti-drive servo mechanism has been developed to eliminate the effect of backlash. A single degree of freedom platform has been constructed with gear reduction

99.231. The selection of DC servomotor has been done by off shelf parts of second hand parts of printers and other electric equipments available in local market. Arrangement of gear selected as following:

Gear 1= 46: 18 gear ratio; Gear 2 = 41: 17 gear ratio

Gear 3= 42: 21 gear ratio; Final Gear1= 161 teeth

Actuator Gear = 20 teeth

Total gear reduction = $N_f / N_1 = 99.231{:}\ 1$

Actuator is Minertia DC brush less motor with a supply of 36 volts DC and a Speed of 2000 rpm. With above specifications the platform can move at angular speed of 120.9 degree per second. This was required to move the camera, tracking a target, in such away that there would be no backlash in the manipulator.

Two sets of motors and gear arrangements have been used to construct the drive/anti-drive mechanism of the manipulator. Figure 3 shows the simple one-DOF gear train with two unidirectional drives, where D1 and D2 are the driving gears and F is the follower.

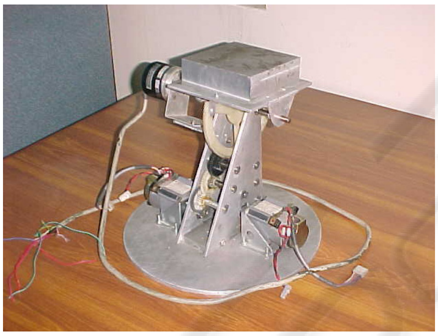

Figure 3: Photographic view of the manipulator.

3.2 Model of the system

Since the system is almost similar in construction and principle as constructed for the 2DOF platform (Tanveer and Masood et al, 2005), but here the only degree of motion is the elevation so using the previous method of Least Squares (Hassan and Askari et al, 2005), the continuous and discrete forms of the model are as follows:

$$J\ddot{x} = -\alpha \cos x - K\dot{x} + \tau \qquad (4)$$

$$x[k] = -\frac{\alpha T^2}{J+kT}\cos x[k] + \frac{2J+kT}{J+kT}x[k-1] - \frac{J}{J+kT}x[k-2] + \frac{T^2}{J+kT}\tau[k] \qquad (5)$$

The parameters of the model are found by giving a persistently exciting chirp signal at input and the system is examined on a desired set of frequencies. The system parameters found are as follows:

J = 2; α = 0.5; K = 0.8

For model validation, a similar model of the system with above parameters was simulated in SIMULINK and both the Simulink and actual model were excited by the same chirp input and response was calculated.

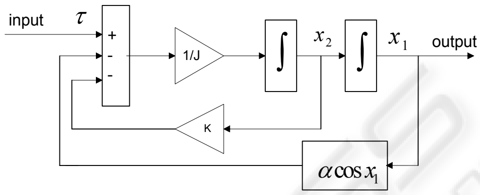

Figure 4: Simulated model for the plant.

The estimate is approximately close to the actual values of the parameters for the desired range of frequencies, as shown in figure 5.

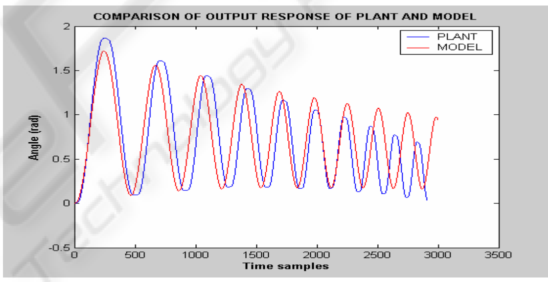

Figure 5: Comparison of output responses of the plant and model simulations.

4 DEADZONE NONLINEARITY

Deadzone nonlinearity (due to backlash), shown in figure 6, causes the reduction in the actuator movement. It is expected in the model whenever there is direction reversal in the actuator.

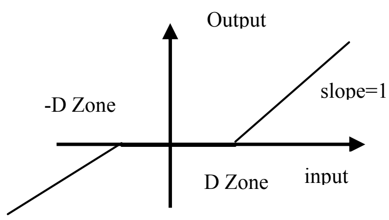

Figure 6: Input-output characteristic curve for deadzone nonlinearity.

We introduce a deadzone nonlinearity of 0.5 in the plant model.
By introducing deadzone function h(.), the model equation will be of the following form:

$$J\ddot{x} = -\alpha \cos x - K\dot{x} + h[\tau] \qquad (6)$$

Where $h[\tau] = \tau - \gamma$ where $\gamma =$ deadzone.

By applying step input, $\ddot{x}$ will be zero at steady state. Hence left hand side of (6) will be zero.
Therefore at steady state

$$\ddot{x} = 0$$

$$\dot{x} = \omega_{ss}$$

Now (6) will become

$$K\omega_{ss} = h(\tau) - \alpha \cos\ x$$

$$\omega_{ss} = \frac{\tau - \gamma - \alpha \cos\ x}{K} \qquad (7)$$

By applying three different values of step input τ, result in giving three values of ω_{ss}. An average of output angle of the manipulator, is taken as output, as x_{av} during the steady state region. Hence three sets of equations results as follows:

$$\tau_1 = K\omega_{ss1} + \gamma + \alpha \cos x_{av1}$$

$$\tau_2 = K\omega_{ss2} + \gamma + \alpha \cos x_{av2} \qquad (8)$$

$$\tau_3 = K\omega_{ss3} + \gamma + \alpha \cos x_{av3}$$

Applying three different values of τ and observing data the values are as following:

$\tau_1 = 5 \quad \omega_{ss1} = 5.65 \quad \theta_{av1} = 111.5\,\text{deg}$

$\tau_2 = 10 \quad \omega_{ss2} = 11.89 \quad \theta_{av2} = 236.05\,\text{deg}$

$\tau_3 = 15 \quad \omega_{ss3} = 18.12 \quad \theta_{av3} = 360.48\,\text{deg}$

Substituting the above values in (8), the estimates are:

$\alpha = 0.0047$; $K = 0.8$ $\gamma = 0.47$

The estimates of K and γ are approximately in acceptable limits, however α is not estimated accurately. It happened because of taking average of output angle in (8). We are not interested in it because α has already been estimated by least-squares method.

5 CONCLUSION

In this paper, we have presented a new concept for controlling gear backlash of an articulated gear mechanism. A high performance single degree of freedom platform has been developed with redundant drives. The concept utilizes redundant unidirectional drives to assure positive coupling of gear meshes at all times. One side-benefit of this class of mechanism is that it is fail safe, i.e., unless there is loss of backlash control, the mechanism can continue to function even when one of its actuator fails to work.

The following simulation shows the result of the removal of backlash in the system. In figure 7a) the platform is controlled by using the drive antidrive mechanism, the deadzone or backlash reduces and there is just a constant output for 12 time samples only. But using one actuator, the output remains constant for approximately 35 data samples at the position of torque reversal. So there is a remarkable improvement in the system response and the effect of backlash has considerably been removed.

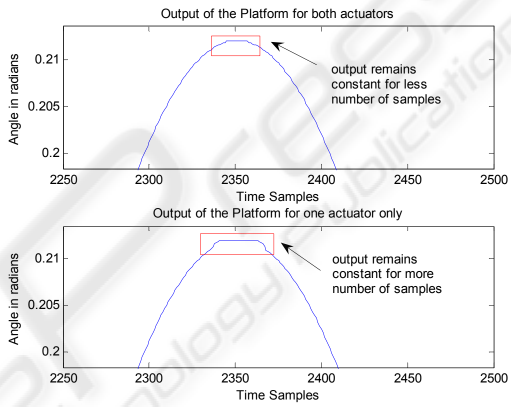

Figure 7: Output response for single and double actuators.

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