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IMPROVING PERFORMANCE IN SINGLE-LINK FLEXIBLE MANIPULATOR USING HYBRID LEARNING CONTROL

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ABSTRACT

An iterative learning control method for a single-link flexible manipulator is proposed to achieve precise tracking control and end-point vibration suppression of the system. The learning is done in a feedback configuration with hybrid control and the learning law updates the feedforward input from the error of the previous trial. The dynamic model of the flexible manipulator is derived using the finite element method. Initially, a collocated proportional-derivative (PD) controller utilizing hub-angle and hub-velocity feedback is developed for control of rigid-body motion of the system. The controller is then extended to incorporate a non-collocated proportional-integral-derivative (PID) controller and a feedforward controller based on input shaping techniques for control of vibration (flexible motion) of the system. Simulation results of the response of the manipulator with the controllers are presented in the time and frequency domains. The performance of the hybrid iterative learning control scheme is assessed in terms of input tracking and level of vibration reduction in comparison to a conventionally designed collocated PD and non-collocated PID control schemes.

***Keywords**: Iterative learning control, PD control, PID control, Input shaping, Flexible manipulator, Vibration control.*

1.0 INTRODUCTION

Many industrial applications of robot manipulators involve iterative or repeated cycles of events. Thus, it is important to minimize errors in trajectory tracking of such manipulators, and this can be achieved with suitable learning strategies. In iterative learning control (ILC), the controller should learn from previous cycles and perform better every cycle. Such ideas were presented by Arimoto *et al.* [1] who proposed a learning control scheme called the improvement process, and since then many papers have addressed robot control in combination with iterative learning control, [2-4]. The convergence properties when using iterative learning control is another very important aspect addressed in [1], and further covered in [5] and [6]. In this paper, ILC is studied as a complement to conventional feedforward and feedback control. Flexible robot manipulators exhibit many advantages over their rigid counterparts: they require less material, are lighter in weight, have higher manipulation speed, require lower power consumption, require smaller actuators, are more manoeuvrable and transportable, are safer to operate due to reduced inertia, have less overall cost and have higher payload to robot weight ratio. However, the control of flexible manipulators to maintain accurate positioning is a challenging task. Due to the flexible nature and distributed characteristics of the system, the dynamics are highly non-linear and complex. Problems arised are due to precise positioning requirements, system flexibility leading to vibration, the difficulty in obtaining accurate model of the system and non-minimum phase characteristics of the system [7].

The complexity of the control problem increases dramatically when a flexible manipulator carries a payload. Practically, robots are required to perform a single or sequential task such as to pick up a payload, move to a specified location along a pre-planned trajectory and place the payload. Previous studies have shown that the dynamic behaviour and vibration of the manipulator were significantly affected by payload variations [8]. Moreover, successful control of a flexible manipulator is contingent upon achieving acceptable uniform performance in the presence of payload variations.

The flexible manipulator motion typically consists of three phases: acceleration, constant speed and deceleration. To attain end-point positional accuracy, a control mechanism that accounts for both the rigid body and flexural motions of the system is required. A constrained planar single-link flexible manipulator is considered in the study. A simulation environment is developed within Simulink® and MATLAB® for evaluation of performance of the control strategies. In this work, the dynamic model of the flexible manipulator is derived using the finite element (FE) method. Previous simulation and experimental studies have shown that the FE method gave an acceptable dynamic characterization of the actual system [9]. Moreover, a single element is sufficient to describe the dynamic behaviour of the manipulator reasonable well.

To demonstrate the effectiveness of the proposed control schemes, initially a joint-based collocated (JBC) PD controller utilizing hub-angle and hub-velocity feedback is developed for the control of rigid-body motion. Later, the controller is extended to incorporate non-collocated and iterative learning control for

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vibration suppression of the manipulator. Simulation results of the response of the manipulator with the controllers are presented in time and frequency domains. The performance of the hybrid control scheme is assessed in terms of input tracking and level of vibration reduction in comparison to the response with PD-PID controller and combination of PD controller and input shaping technique.

2.0 THE FLEXIBLE MANIPULATOR SYSTEM

A schematic representation of the single-link flexible manipulator system is shown in Figure 1, where a control torque $\tau(t)$ is applied at the hub by an actuator motor with E, I, ρ, L, I_H and M_p represent Young's modulus, moment of inertia, mass density per unit volume, length, hub inertia and payload of the manipulator respectively. The angular displacement of the link in the POQ co-ordinates is denoted as $\theta(t)$. w represents the elastic deflection of the manipulator at a distance x from the hub, measured along the OP' axis. POQ and P'OQ' represent the stationary and moving frames respectively.

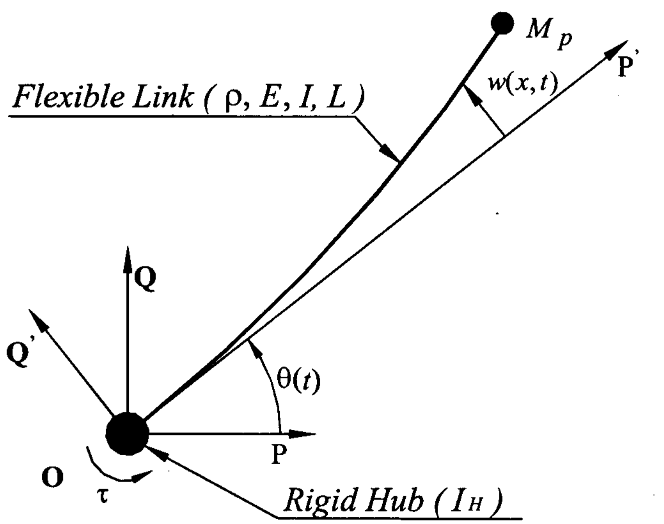


Figure 1 A schematic representation of the single-link flexible manipulator.

The height (width) of the link is assumed to be much greater than its depth, thus allowing the manipulator to vibrate dominantly in the horizontal direction (POQ plane). To avoid difficulties arising from time varying lengths, the length of the manipulator is assumed to be constant. Moreover, the shear deformation, rotary inertia and the effect of axial force are ignored. For an angular displacement θ and an elastic deflection w, the total displacement $y(x,t)$ of a point along the manipulator at a distance x from the hub can be described as a function of both the rigid body motion $\theta(t)$ and elastic deflection $w(x,t)$, i.e.

$$y(x,t) = x\theta(t) + w(x,t) \tag{1}$$

Thus, the net deflection at x is the sum of a rigid body deflection and an elastic deflection. By allowing the manipulator to be dominantly flexible in the horizontal direction, the elastic deflection of the manipulator can be assumed to be confined to the horizontal plane only. In general, the motion of a manipulator includes elastic deflection in both the vertical and horizontal planes. Motion in the vertical plane due to gravity forces can cause permanent elastic deflections. However, this effect is neglected in this study as the manipulator is assumed to be dominantly flexible in the horizontal plane.

In this study, an aluminium-type flexible manipulator of dimension 900 mm × 19.008 mm × 3.2004 mm with $E = 71\times10^9$ N/m^2, $I = 5.253\times10^{-11}$ m^4 and $I_H = 5.8598\times10^{-4}$ kgm^2 is considered. Further details of the derivation of the dynamic equations of the flexible manipulator using the FE method can be found in [7].

3.0 CONTROL STRATEGIES

In this section, iterative learning control (ILC) as a complement to the conventional feedforward and feedback control is proposed. The aim is to illustrate the fundamental properties of the ILC algorithm applied in this framework, with focus on an input tracking and vibration suppression capability. Initially, a collocated PD control is designed. Then a non-collocated PID control and feedforward control based on input shaping method are incorporated in the closed-loop system for the control of vibration of the system.

3.1 Collocated PD control

A common strategy in the control of manipulator systems involves the utilization of PD feedback of collocated sensor signals and is adopted at the initial stage of the investigation. A block diagram of the PD controller is shown in Figure 2, where K_p and K_v are the proportional and derivative gains respectively, θ, $\dot{\theta}$ and α represent hub angle, hub velocity and end-point residual respectively, R_f is the reference hub angle and A_c is the gain of the motor amplifier. The motor/amplifier set is considered as a linear gain A_c.

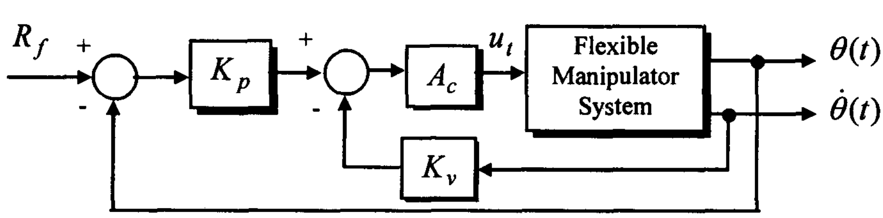


Figure 2 The collocated PD control structure

To design the PD controller, a linear state-space model of the flexible manipulator was obtained by linearizing the equations of motion of the system. The first two flexible modes of the manipulator were assumed to be dominantly significant. The control signal u_t in Figure 2 can thus be written in Laplace domain as

$$u(s) = A_c[K_p\{R_f(s) - \theta(s)\} - K_v\dot{\theta}] \tag{2}$$

where s is the Laplace variable. The closed-loop transfer function is therefore obtained as

$$\frac{\theta(s)}{R_f(s)} = \frac{K_p H(s) A_c}{1 + A_c K_v (s + K_p/K_v) H(s)} \tag{3}$$

where $H(s)$ is the open-loop transfer function from the input torque to hub angle, given by

$$H(s) = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} \tag{4}$$

where $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ are the characteristic matrix, input matrix and output matrix of the system respectively and $\mathbf{I}$ is the identity matrix. The closed-loop poles of the system are given by the closed-loop characteristic equation as

$$1 + K_v(s + Z)H(s)A_c = 0 \tag{5}$$

where $Z = K_p/K_v$ represents the compensator zero which determines the control performance and characterises the shape of root locus of the closed-loop system. It is well known that theoretically any choice of the gains K_p and K_v assures the stability of the system [10]. In this study, the root locus approach is utilized to design the PD controller. Analyses of the root locus plot of the system shows that dominant poles with maximum negative real parts could be achieved with $Z \approx 2$ and by setting K_p between 0 and 1.2 [7].

3.2 Hybrid Collocated PD and PID Control

The use of a non-collocated control system, where the end-point of the manipulator is controlled by measuring its position, can be applied to improve the overall performance, as more reliable output measurement is obtained. The control structure comprises two feedback loops: a) the hub angle and hub velocity as inputs to a collocated control law for rigid-body motion control; b) the end-point residual (elastic deformation) as input to a separate non-collocated control law for vibration control. These two loops are then summed together to give a torque input to the system. A block diagram of the control scheme is shown in Figure 3, where r_α represents the end-point residual reference input, which is set to zero as the control objective is to have zero vibration during movement of the manipulator. For rigid-body motion control, the PD control strategy developed in the previous section is adopted whereas for the vibration control loop, the end-point residual feedback through a PID control scheme is utilized. The values of proportional (P), derivative (D) and integral (I) gains are adjusted using the Ziegler-Nichols procedure [11].

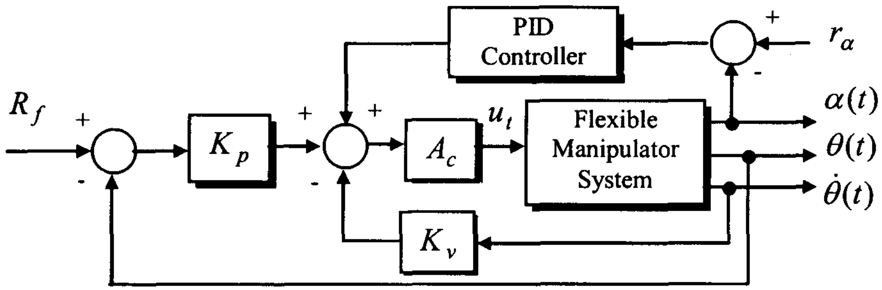


Figure 3 The collocated PD and non-collocated PID control structure

3.3 Hybrid Collocated and Non-Collocated Controller with Iterative Learning Control

A hybrid collocated PD and non-collocated PID control structure for control of rigid-body motion and vibration suppression of the flexible manipulator with iterative learning control is proposed in this section. In this study, iterative learning control scheme is developed using PD-type learning algorithm.

Iterative learning control (ILC) has been an active research area for more than a decade, mainly inspired by the pioneering work of Arimoto *et al.* [12-14]. Learning control begins with the fundamental principle that repeated practice is a common mode of human learning. Given a goal (regulation, tracking, or optimization), learning control, or more specifically, iterative learning control refers to the mechanism by which necessary control can be synthesized by repeated trials. Iterative learning control is defined as an approach to improve the transient response performance of a system that operates repetitively over a fixed time interval [12]. The concept of iterative learning control was motivated through observing the behaviour of dynamic systems and also analysing the problems in which a system must have the capability to accurately respond to several different types of inputs. Uchiyama first introduced the concept of iterative learning for generating the optimal input to a system [13]. Later, Arimoto and his co-workers developed the idea [12-14]. Figure 4 illustrates the basic idea of an iterative learning control.

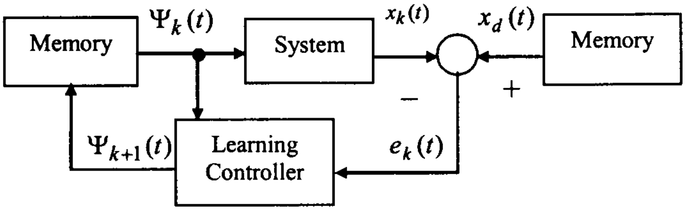


Figure 4 Iterative learning control configuration

The input signal $\Psi_k(t)$ and output signals $x_k(t)$, are stored in memory where some type of memory device is implicitly assumed in the block labeled "learning controller". By using the desired output of the system $x_d(t)$ and the actual output $x_k(t)$, the performance error at k th trial can be defined as:

$$e_k(t) = x_d(t) - x_k(t) \tag{6}$$

The aim of iterative learning control is to iteratively compute a new compensation input signal $\Psi_{k+1}(t)$, which is stored for use in the next trial. The next input command is chosen in such a way as to guarantee that the performance error will be reduced in the next trial. Thus, the important task in the design of a learning controller is to find an algorithm for generating the next input in such a way that the performance error is reduced on successive trials. In other words, the algorithm needs to lead to the convergence of the error to minimum. Another consideration is that it is desirable to have the convergence of the error without or at least with minimal knowledge of the model of the system. Further, the algorithm should be independent of the functional form of the desired response, $x_d(t)$. Thus, the learning controller would "learn" the best possible control signal for a particular desired output trajectory even if it is newly introduced without the need to reconfigure the algorithm.

Most of the algorithms described by Arimoto *et al.* [12-14] have a structure of the following form: the $(k+1)$ th input to a system consists of a k th input plus an error increment which may be composed of a derivative difference between the k th motion trajectory and the given desired motion trajectory, an integral of the difference of the trajectory and/or simply a constant coefficient [15]. A typical learning algorithm is given by the equation:

$$\Psi_{k+1} = \Psi_k + \Phi e_k + \Gamma \dot{e}_k \tag{7}$$

where

Ψ_{k+1} is the next control signal

Ψ_k is the current control signal

e_k is the current positional error input, $e_k = (x_d - x_k)$

Φ and Γ are suitable positive definite constants (or learning parameters)

A PD type algorithm is represented in Figure 5 while a block diagram of the control scheme is shown in Figure 6.

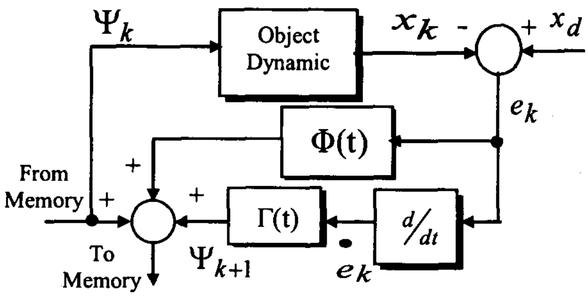


Figure 5 PD type learning algorithm

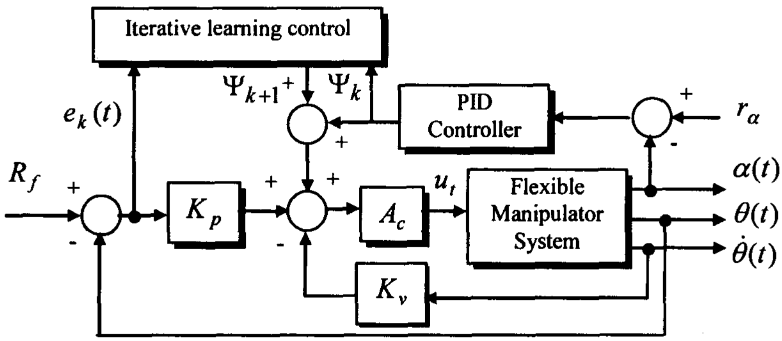


Figure 6 The collocated PD and non-collocated PID control structure with iterative learning

3.4 Hybrid PD and Feedforward Control

A hybrid control structure for control of rigid body motion and vibration suppression of the flexible manipulator based on a collocated PD and feedforward control is proposed in this section. In this study, the feedforward control scheme is developed using an input shaping technique with a four-impulse sequence. Previous experimental study on a flexible manipulator has shown that significant vibration reduction and robustness was achieved using a four-impulse sequence technique [16]. A block diagram of the control scheme is shown in Figure 7.

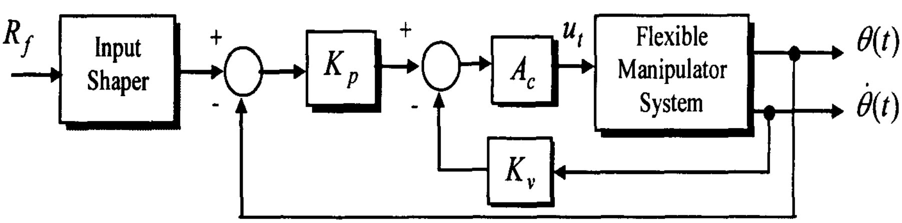


Figure 7 The collocated PD and feedforward control structure

The input shaping method involves convolving a desired command with a sequence of impulses known as input shaper. The design objectives are to determine the amplitude and time location of the impulses based on the natural frequencies and damping ratios of the system. The corresponding design relations for achieving zero residual single mode vibration that ensures the shaped command input produces the same rigid body motion as the unshaped command, yields a two-impulse sequence with parameters as

$$t_1 = 0, \quad t_2 = \frac{\pi}{\omega_d}, \; A_1 = \frac{1}{1+H}, \quad A_2 = \frac{H}{1+H}. \tag{8}$$

where ω_n and ζ represent the undamped natural frequency and damping ratio respectively with

$$H = e^{-\frac{\zeta\pi}{\sqrt{1-\zeta^2}}} \text{ and } \omega_d = \omega_n\sqrt{1-\zeta^2} \tag{9}$$

where t_j and A_j are the time location and amplitude of impulse j respectively. The robustness of the input shaper to errors in natural frequencies of the system can be increased by solving the derivatives of the system vibration equation. This yields a four-impulse sequence with parameters as

$$t_1 = 0, \quad t_2 = \frac{\pi}{\omega_d}, \quad t_3 = \frac{2\pi}{\omega_d}, \quad t_4 = \frac{3\pi}{\omega_d},$$

$$\begin{aligned} A_1 &= \frac{1}{1+3H+3H^2+H^3}, \quad A_2 = \frac{3H}{1+3H+3H^2+H^3}, \\ A_3 &= \frac{3H^2}{1+3H+3H^2+H^3}, \quad A_4 = \frac{H^3}{1+3H+3H^2+H^3}. \end{aligned} \tag{10}$$

To handle higher vibration modes, an impulse sequence for each vibration mode can be designed independently. Then the impulse sequences can be convoluted together to form a sequence of impulses that attenuate vibration at higher modes. In this manner, the vibration reduction can be accomplished by convolving a desired reference input with the input shaper. This yields a shaped input that drives the system to a desired location with reduced vibration.

4.0 SIMULATION RESULTS AND DISCUSSION

In this section, the proposed control schemes are implemented and tested within the simulation environment of the flexible manipulator and the corresponding results are presented. The manipulator is required to follow a trajectory at ±80° as shown in Figure 8. System responses, namely the hub angle, hub velocity and end point residual, are observed. To investigate the vibration of the system in the frequency domain, power spectral density (SD) of the response at the end-point is obtained. The performances of the hybrid learning controllers are assessed in terms of input tracking and vibration suppression in comparison to the PDPID and PD with input shaping control (PDIS) considering with and without payload.

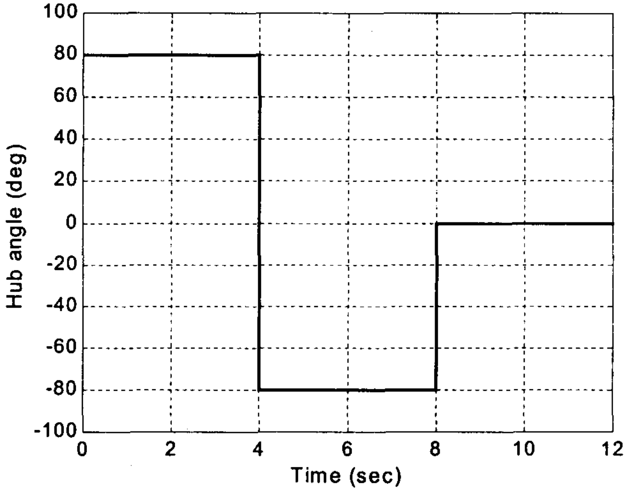
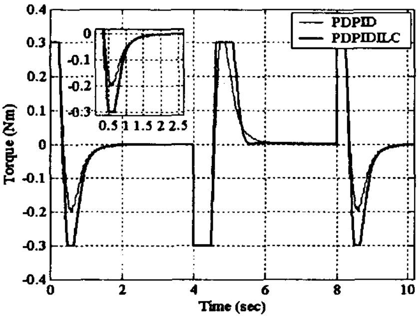
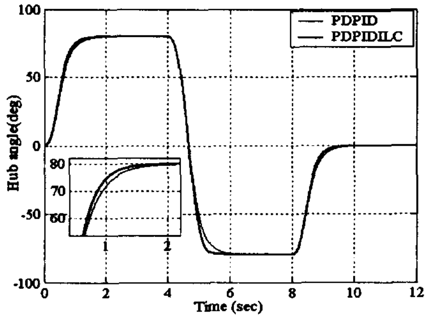


Figure 8 The reference hub angle.

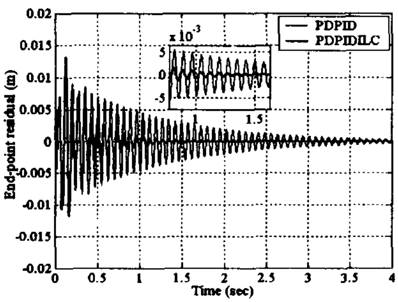
In the collocated PD and non-collocated PID (PDPID) control scheme, the design of PD controller was based on root locus analysis, from which K_p, K_v and A_c were deduced as 0.64, 0.32 and 0.01 respectively. The PID controller parameters were tuned using the Ziegler-Nichols method using a closed-loop technique where the proportional gain was initially tuned and the integral gain and derivative gain were then calculated [11]. Accordingly, the P, I and D parameters were deduced as 0.1, 70 and 0.01 respectively. To decouple the end-point measurement from the rigid-body motion of the manipulator, a fourth-order infinite impulse response (IIR) Butterworth high-pass filter was utilized. In this investigation, a high-pass filter with a cut-off frequency of 5 Hz was designed as the first vibration mode of the system with a payload was obtained as 10 Hz. The corresponding system response with the PDPID control (with and without payload) is shown in Figures 9 and 10. It is noted that the manipulator reached the required position of $\pm 80°$ within 4s, with no significant overshoot. However, a noticeable amount of vibration occurs during movement of the manipulator. It is noted from the end-point residual that the vibration of the system settles within 4s with a maximum residual of ± 0.015m. Moreover, the vibration at the end-point was dominated by the first three vibration modes, which are obtained as 13, 35 and 63 Hz without payload and 11.9, 32.7, 59.5 Hz with a 20 g payload. The flexible manipulator is set with a structural damping of 0.026, 0.038 and 0.04 for the first, second and third vibration modes respectively.



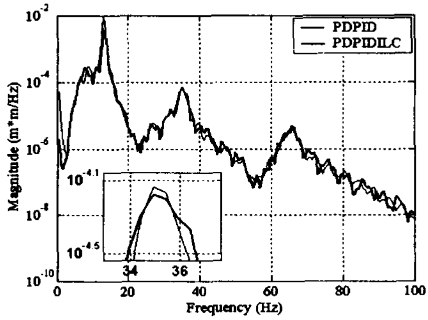
(a) Torque input



(b) Hub-angle

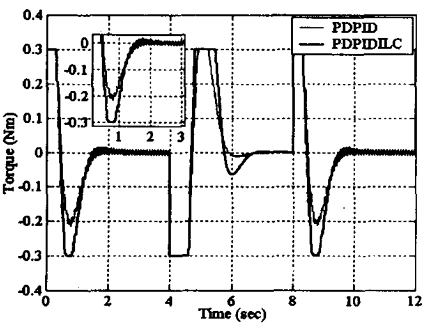


(c) End-point residual
(time domain)

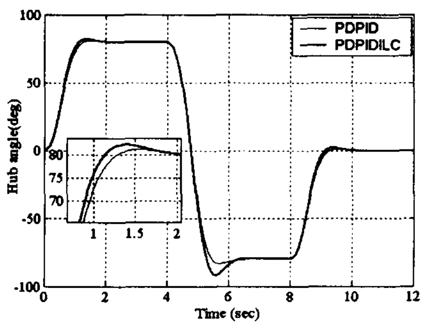


(d) End-point residual
(frequency domain)

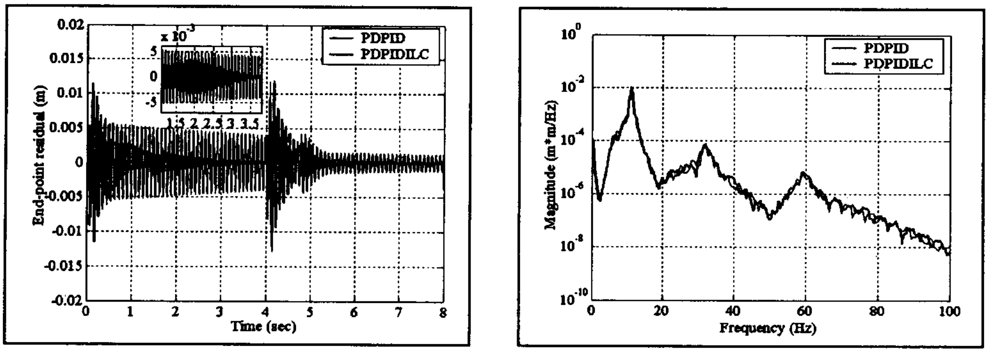
Figure 9 Response of the flexible manipulator with PDPID and PDPIDILC without payload



(a) Torque input



(b) Hub-angle

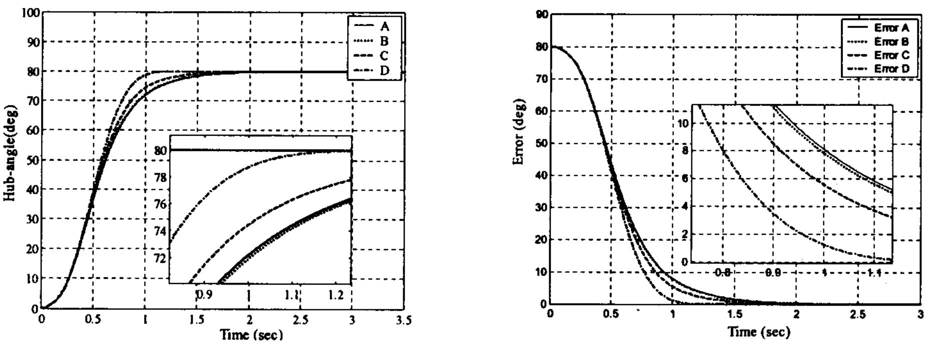


(c) End-point residual
(time domain)

(d) End-point residual
(frequency domain)

Figure 10 Response of the flexible manipulator with PDPID and PDPIDILC with 20g payload

The hybrid learning control scheme (PDPIDILC) as shown in Figure 3 was designed on the basis of the dynamic behaviour of the closed-loop system. The parameters of the learning algorithm, Φ and Γ were tuned heuristically over the simulation period and were deduced as 0.003 and 0.0001 respectively. Figures 9 and 10 show the corresponding responses of the manipulator without payload and a 20 g payload for both PDPID and PDPIDILC schemes while Figure 11 shows the hub-angle and error signal for different values of parameter Φ (A=0, B=0.0015, C=0.001 and D=0.003).



(a) Hub-angle

(b) Error signal

Figure 11 The response of hub-angle and error signal for different values of Φ (A=0, B=0.0001, C=0.001 and D=0.003)

The result show that the proposed hybrid controller with learning algorithm (PDPIDILC) is capable of reducing the system vibration and resulting in better input tracking performance of the manipulator. The vibration of the system settled within less than 0.3 s as compared to PDPID control of 0.4s. It is also noted that, the time response for PDPIDILC controller with payload is faster compared to the PDPID counterpart. It shows that the controller is able to handle vibration of the manipulator with a payload, as significant reduction in system vibration was observed. Furthermore, the closed-loop system response required only 0.4 s to settle down.

In the case of hybrid collocated and feedforward control scheme (PDIS), an input shaper was designed based on the dynamic behaviour of the closed-loop system obtained using only the PD control. The natural frequencies of the manipulator were determined as 12, 35 and 65 Hz without payload. Previous experimental results have shown that the damping ratio of the flexible manipulator ranges from 0.024 to 0.1 [7]. In this work, the damping ratios were deduced as 0.026, 0.038 and 0.05 for the first three modes respectively. The magnitudes and time locations of the impulses were obtained by solving equation (10) for the first three modes. For digital implementation of the input shaper, locations of the impulses were selected at the nearest sampling time. The developed input shaper was then used to pre-process the input reference as shown in Figure 8. Figure 12 shows the resulting torque input that drives the manipulator without payload with PDIS and PDPIDILC control.

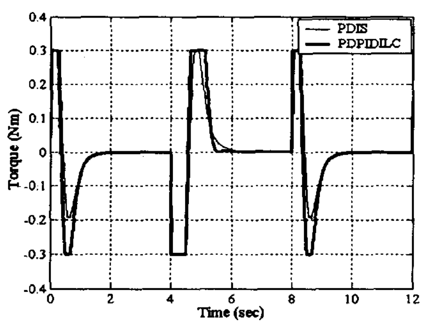
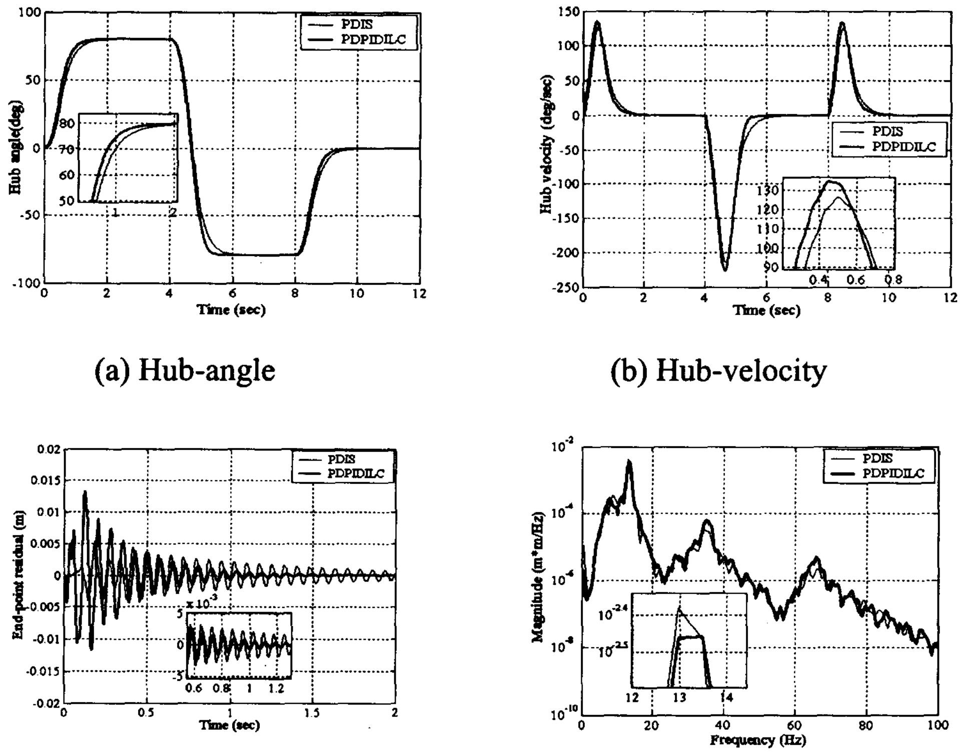


Figure 12 Torque input with PDIS and PDPIDILC

The corresponding responses of the manipulator are shown in Figure 13. It is noted that the proposed hybrid learning control is capable of reducing the system vibration while resulting in better input tracking performance of the manipulator. The vibration of the system settled within less than 1.5 s as compared to PDIS control.

However, the implementation of hybrid PDPIDILC takes more time compared to PDPID and PDIS as a large amount of design effort is required to determine the best learning parameters. An automatic tuning of the learning parameters could produce better results. As demonstrated in the hub-angle and end-point residual response, a slightly better response is obtained with the PDPIDILC controller as shown in Figures 13 (a) and (c). The approach thus developed and reported in this paper forms the concept of design and development of hybrid learning control schemes for input tracking and vibration suppression of flexible manipulator systems and can be extended to and adopted in practical applications.



(a) Hub-angle

(b) Hub-velocity

(c) End-point residual (time domain)

(d) End-point residual (frequency domain)

Figure 13 Response of the flexible manipulator with PDIS and PDPIDILC

5.0 CONCLUSION

An iterative learning control strategy for flexible manipulator systems has been presented. The control strategies developed through combination of collocated PD and non-collocated PID with iterative learning control (PDPIDILC) and collocated PD with feebforward control based on the input shaping technique (PDIS) have been reported. The proposed control schemes have been implemented and tested within simulation environment of a single-link flexible manipulator. The performances of the control schemes have been evaluated in terms of input tracking capability and vibration suppression at the resonance modes of the manipulator. Acceptable input tracking control and vibration suppression have been achieved with both PDPIDILC and PDIS control strategies. A comparative assessment of the control technique has shown that hybrid PDPIDILC scheme results in better performance than the PDIS counterpart with respect to the hub-angle and vibration reduction at the end-point of the manipulator.

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