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HYBRID ITERATIVE LEARNING CONTROL OF A FLEXIBLE MANIPULATOR

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ABSTRACT

This paper presents an investigation into the development of a hybrid control scheme with iterative learning for input tracking and end-point vibration suppression of a flexible manipulator system. The dynamic model of the system is derived using the finite element method. Initially, a collocated proportional-derivative (PD) controller using hub angle and hub velocity feedback is developed for control of rigid-body motion of the system. This is then extended to incorporate a non-collocated proportional-integral-derivative (PID) controller with iterative learning for control of vibration 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 PD-PID control scheme. The effectiveness of the control scheme in handling various payloads is also studied.

Keywords: Flexible manipulator, hybrid control, iterative learning.

1 INTRODUCTION

Flexible manipulator systems offer several advantages over their traditional counterparts: they are lighter in weight, have faster response, consume less power, require smaller actuators, are more manoeuvrable, are more transportable, have reduced non-linearity owing to elimination of gearing, are safer to operate due to reduced inertia and, in general, have less overall cost [1,2]. However, the control of flexible manipulators is made complicated by the highly non-linear dynamics of the system which involve complex processes. If the advantages associated with light weight are not to be sacrificed, efficient controls have to be studied and developed.

Feedback control techniques use measurement and estimates of the system states for control of rigid-body motion and vibration suppression. In this case, using measurements at the hub and end-point of the manipulator as the basis for applying control torque at the hub will allow control of the end-point position. Thus, feedback control can be divided into collocated and non-collocated schemes. An important aspect of the flexible manipulator control that has received little attention is the interaction between the rigid and flexible dynamics of the links. An acceptable system performance with reduced vibration that accounts for system changes can be achieved by developing a hybrid control scheme that caters for rigid body motion and vibration of the system independently. Previously, a hybrid collocated and non-collocated controller has been proposed [1]. This utilizes end-point acceleration feedback through a proportional-integral-derivative (PID) control scheme for vibration reduction and hub angle and hub velocity feedback through a proportional-derivative (PD) control scheme for rigid-body motion control. Experimental works have shown that this control structure performs better in respect of vibration reduction than a collocated controller.

This paper presents investigations into the development of hybrid control with learning algorithm schemes for flexible manipulators. A constrained planar single-link flexible manipulator is considered. 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 gives an acceptable dynamic characterization of the actual system [3]. Moreover, a single element is sufficient to describe the dynamic behaviour of the manipulator reasonably 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 control of rigid-body motion. This is then extended to incorporate non-collocated and iterative learning control for vibration suppression of the manipulator. Simulation results of the response of the manipulator with the controller 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 control. As the dynamic behaviour of the system changes with different payloads, the effectiveness of the controller is also studied with different loading conditions.

2 THE FLEXIBLE MANIPULATOR SYSTEM

The 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 and E, I, ρ, V, I_h and M_p represent Young's modulus, moment of inertia, mass density per unit volume, cross-sectional area, hub inertia and payload of the manipulator respectively. The angular displacement of the link in the POQ co-ordinates is denoted as $\theta(t)$. u 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.

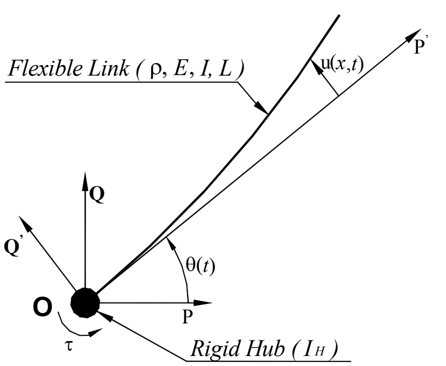


Figure 1: The schematic representation of the single-link flexible manipulator.

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 u, 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 $u(x,t)$,

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

Thus, the net deflection at x is the sum of a rigid body deflection and an elastic deflection. Note that 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 will include elastic deflection in both, the vertical and horizontal planes. Motion in the vertical plane as a result of gravity forces for example, can cause permanent elastic deflections. This effect is neglected here as the manipulator is assumed to be dominantly flexible in the horizontal plane. In this study, an aluminium-type flexible manipulator of dimensions $900mm \times 19.008mm \times 3.2004mm$, $E = 71\times10^9\ N/m^2$, $I = 5.253\times10^{-11}\ m^4$ 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 [3].

3 CONTROL SCHEMES

In this section, control schemes for rigid-body motion control and vibration suppression of the flexible manipulator are introduced. Initially, a collocated PD control is designed. Then a non-collocated PID control without and with iterative learning control (ILC) in the closed-loop system for control of vibration of the system is designed.

3.1 Hybrid PD Control and Non-Collocated PID Control

A common strategy in the control of manipulator systems involves the utilization of PD feedback of collocated sensor signals. Such a strategy is adopted at this stage of the investigation here. 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 acceleration respectively, R_f is the reference hub angle and A_c is the gain of the motor amplifier. Here the motor/amplifier set is considered as a linear gain A_c, as the set is found to function linearly in the frequency range of interest. 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 $u(s)$ in Figure 2 can thus be written 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

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

where A, B and C are the characteristic matrix, input matrix and output matrix of the system respectively and I is the identity matrix. The closed-loop poles of the system are, thus, 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 gain K_p and K_v assures the stability of the system [4]. 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 [1]. 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 2, 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.

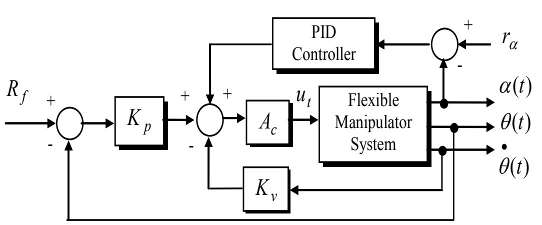


Figure 2: The collocated PD and non-collocated PID control

3.2 Hybrid Collocated 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, [5,6,7,8]. Learning control begun 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. A typical learning algorithm is given by the equation:

$$u_{k+1} = u_k + \Phi e_k + \Gamma \dot{e}_K \tag{6}$$

where

u_{k+1} is the next output signal

u_k is the current output signal

e_k is the current positional error input, $e_k = (x_d - x_k)$ Φ, Γ, Ψ are suitable positive definite constants (or learning parameters)

A slightly modified learning algorithm to suit the application is employed here. Instead of using the absolute positional track error e_k, a sum-squared track error e_k is used.

A PD type algorithm may be represented as shown in Figure 3.

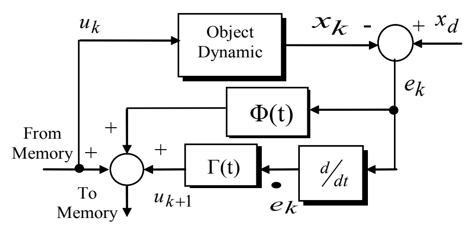
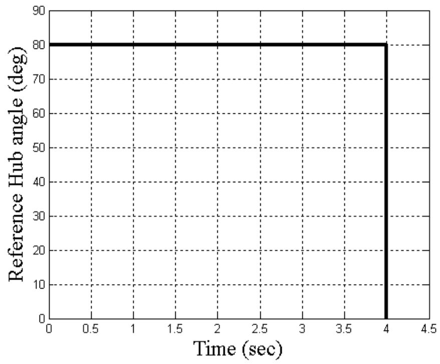


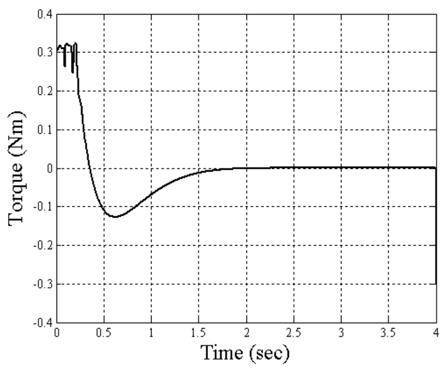
Figure 3: PD type learning algorithm

4 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 $+80^0$ as shown in Figure 4. System responses, namely the hub angle and end-point acceleration 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.



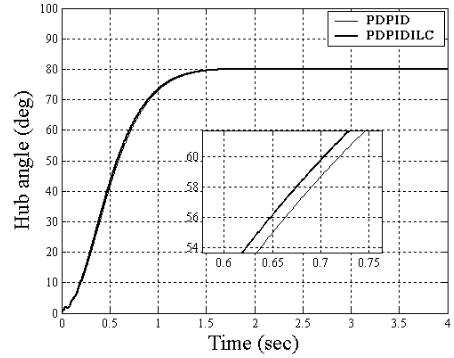
4 (a) The reference hub angle



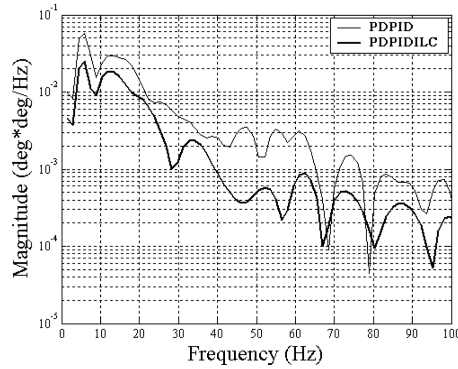
4 (b) Torque input

Figure 4 : The reference hub angle and torque input

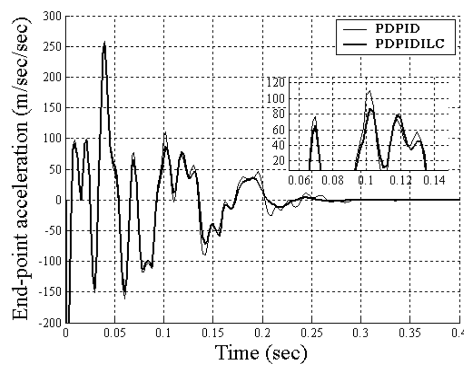
In the collocated and non-collocated control scheme of PD-PID (PDPID), the design of PD controller was based on root locus analysis, from which K_p, K_v and A_c were deduced as 0.64, 0.32 and 0.01 respectively. The PID controller parameters were tuned using the Ziegel-Nichols method where the proportional gain K_p was initially tuned and the integral gain K_i and derivative gain K_d were then calculated [9]. Accordingly, the PID parameters K_p, K_i and K_d were deduced as 0.5, 4 and 0.01 respectively. The corresponding system response with the PD-PID control is shown in Figure 5 and 6. It is noted that the manipulator reached the required position of $+80^0$ within 4 s, with no significant overshoot. A smooth hub velocity profile is observed with a maximum speed of 114 deg/s, achieved within 0.35 s. However, a noticeable amount of vibration occurs during movement of the manipulator. It is noted from the end-point acceleration that the vibration of the system settles within 4 s with a maximum residual of ± 0.01 m. Moreover, the vibration at the end-point was dominated by the first three vibration modes, which are obtained as 13, 33 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.



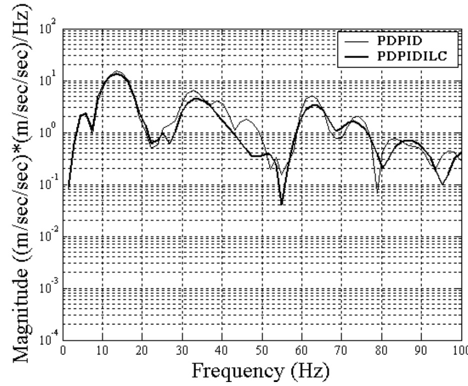
Time domain (hub angle)



Frequency domain (hub angle)

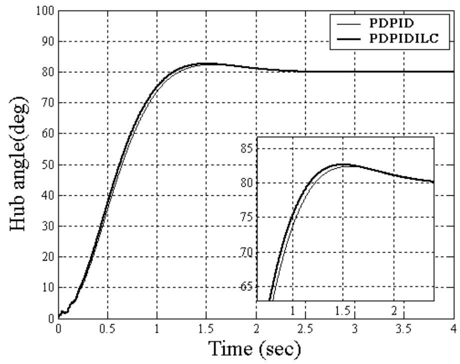


Time domain (end-point)

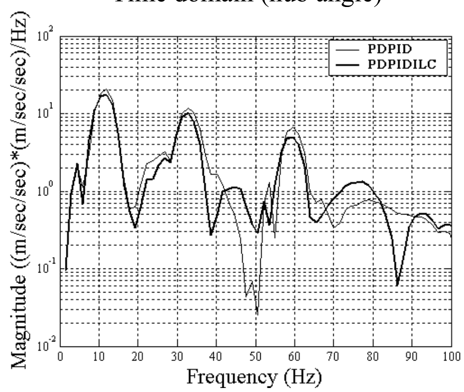


Frequency domain (end-point)

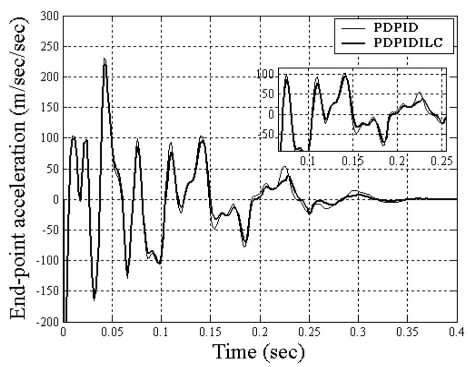
Figure 5: Hub angle and end-point system response without payload



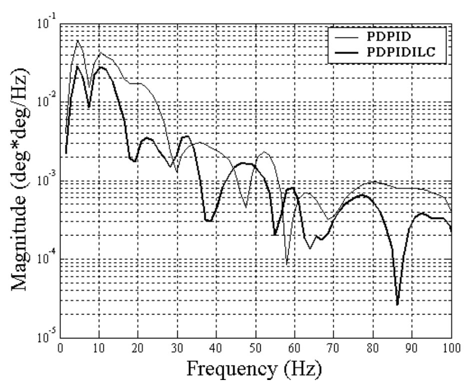
Time domain (hub angle)



Frequency domain (hub angle)



Time domain (end-point)



Frequency domain (end-point)

Figure 6: Hub angle and end-point system response with 20 g payload

The hybrid control with iterative learning control scheme (PD-PID-ILC), shown in Figure 7 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 0.00015 and 0.001 respectively. Figures 5 and 6 show the corresponding responses of the manipulator without payload and a 20 g payload with PD-PID and PD-PID-ILC. It is noted that the proposed hybrid controller with learning algorithm 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 0.3 s as compared to PD-PID control. It is noted that, with payload the time response is faster compared to the PD-PID controller. The controller is found to be 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. This is further evidenced in Figure 8, which demonstrate the level of vibration reduction at the resonance modes of the closed-loop system with the hybrid PD-PID-ILC as compared to that with the hybrid PD-PID controller without payload and with a 20 g payload. It is noted that PD-PID-ILC controller achieved better result with vibration reduction of the system at the resonance modes. Moreover, implementation of hybrid PD-PID-ILC takes more time than PD-PID as a large amount of design effort is required to determine the best learning parameters. Note that a properly automatic tuning of the learning parameters could produce better results. As demonstrated in the hub angle response, a slightly better response is obtained with the PD-PID-ILC. The work thus developed and reported in this paper forms the basis of design and development of hybrid control with learning algorithm schemes for input tracking and vibration suppression of flexible manipulator systems and can be extended to and adopted in practical applications.

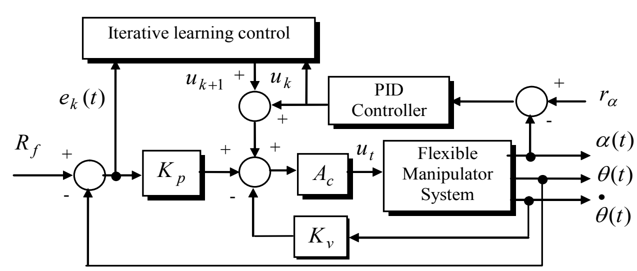


Figure 7: The collocated PD non-collocated PID control structure with iterative learning control

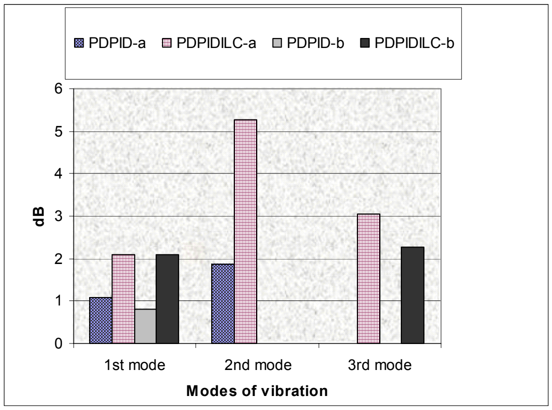


Figure 8: Level of vibration reduction with PDPID and PDPIDILC control at the end-point of the manipulator: (a) 0 g, (b) 20 g

5 CONCLUSION

The development of hybrid control with iterative learning for a flexible manipulator has been presented. The control scheme has been developed on the basis of collocated PD with non-collocated PID and with iterative learning. The control schemes have been implemented and tested within the simulation environment of a single-link flexible manipulator without and with a payload. 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 control strategies. A comparative assessment of the control technique has shown that hybrid PD-PID-ILC scheme results in better performance than the PD-PID control in respect of hub angle response of the manipulator.

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