Proceedings of the World Congress on Engineering and Computer Science 2012 Vol II
WCECS 2012, October 24-26, 2012, San Francisco, USA

Direct Adaptive Hybrid PD-PID Controller for Two-Link Flexible Robotic Manipulator

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Abstract—**A simple and efficient adaptive control scheme is developed to automatically tune PD control gains for two-link flexible manipulator. The manipulator is modeled using Lagrange and assume mode method. The adaptive algorithm is developed for hybrid PD-PID controller in which the PD controller is for rigid body motion control and the PID is for end-point vibration suppression. The simple adaptive control scheme continuously tunes only the proportional and derivative gains of the PD controller depending on the error value without switching. The proposed control law is tested in Matlab/simulink simulation environment. The effect of white noise and rectangular wave disturbance on the proposed controller is extensively studied. Also, effect of changing input signal is also investigated. Performance of the proposed controller is compared with hybrid PD-PID controller in terms of input tracking and vibration suppression. The results show the effectiveness of the proposed direct adaptive hybrid PD-PID controller.**

Index Terms— **controls, PD Control, PID control, flexible manipulator systems**

I. Introduction

Owing to the increase in industrial automation, hazardous terrestrial application, space and deep sea exploration, it became imperative for the robotic manipulator to be lighter in weight to reduce energy consumption, for faster motion and to meet space requirement on weight issues [1-3]. This has resulted in flexibility of the manipulator which has become too complex to model accurately. Tracking control of a two-link flexible manipulator is very challenging, due to vibration of the links in operational space [4]. Various control techniques have been applied to flexible manipulator systems (FMSs) in literature; they include: Proportional-integral-derivative (PID), adaptive, optimal, and robust control [1-6]. Dynamic behaviour of FMS is described using partial differential equation. FMSs are an infinite dimensional distributed parameter system with nonminimum phase property [5]. The infinite dimensional model has to be truncated to reduce the complexity of the control system design. This truncation introduces error in multitudes in real application. This unmodelled part will degrade any model based controller. In addition to the effect of unmodeled part, changing operation condition will also cause the fixed gain controller to break down in operation.

PID controller is still the most widely used industrial controller today [6]. PID controllers are simple, robust over a wide range of operating condition, and easy to implement [7]. Many PID based control schemes have been reported in literature [8- 12]. Performance of fixed-gain PID controllers is limited in real time operations of robot motion. With fixed-gain controller, steady state error will continue to be present if there is disturbance on the system. High gain can reduce this error but can't eliminate it due to the effect of unmoldelled dynamics in high order deformation modes and limit of actuator power [19]. A number of adaptive approaches have been proposed in literature [4, 20] to take care of shortcomings of the fixed-gain PID controllers. The basic idea behind adaptive control technique is that any structured (system parameter) and unstructured (working environment) uncertainties which can degrade the fixed-gain PID controller is estimated in advance and compensated or adjust the gains to council their effect. Lots of disturbances come in to play when FMSs robot is in operation so, in order to attain input tracking accuracy, a controller that will account for the rigid and flexible motion and at the same time able to cope with operational and system uncertainties needs to be developed [21]. In controller design, trade offs are often required because there are usually contradicting performance requirement. For example if high accuracy is desired, high speed of performance has to be given up. To be able to achieve a balance between high accuracy and high speed systematic gain adjustment to error is the solution as proposed in this study.

Becedas *et al.* [22] developed adaptive generalised proportional integral control scheme with online identification to estimate and compensate uncertain parameters for a single link flexible manipulator. Maouche and Attari [23] proposed an adaptive algorithm based on Cerebellar Model Articulation Controller (CMAC) neural network to compensate disturbances in single link flexible manipulator. Dogan *et al.,* [24] proposed an adaptive control scheme for two-link flexible manipulator using adaptive internal model approach. Tinkir *et al.,* [25] proposed an observer based adaptive control scheme using adaptive network based fuzzy logic control technique for a single link flexible robot carrying pendulum. A direct adaptive algorithm using Neural network (NN) was proposed for a class of affine nonlinear systems with partially known and completely unknown system [26]. In this study, a simple direct adaptive control scheme is developed for two-link flexible manipulator with unknown disturbance and changing input signal. The dynamic model of the system is developed using Lagrange and Assume mode method developed by [27]. A hybrid proportional Derivative (PD) - PID with adaptive scheme on the PD gains is proposed. This work improves the performance of PD-PID controller in [28]. The PD control law is applied at the joint for rigid body motion control through the hub angle and joint velocity

Manuscript received May 21, 2012; revised July 20, 2012. This work was supported by the Schlumberger Foundation Faculty for the Future (FFTF)

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feedback. The PID uses the end-point acceleration feedback for vibration control. The adaptive control scheme which is the focus of this study is applied to only the PD controller which acts on the joint error to reject disturbances and to cope with set-point changes. A fast adaptive scheme is proposed that constantly adjust the Proportional and derivative gains in the PD controller. Performance of the proposed controller is studied through simulation in Matlab/Simulink environment. The performance is compared with Hybrid PD-PID controller; effect of white noise and sine wave disturbances on the proposed controller is also studied. Effect of changing the input signal on the proposed controller in investigated. The results are presented and discussed in detail.

The rest of the paper is organised as follows: the dynamics of the system is presented in section 2. The controllers' design schemes are presented in Section 3. Simulation results and discussion are presented in section 4. The concluding remark is given in section 5.

II. MATHEMATICAL MODELLING

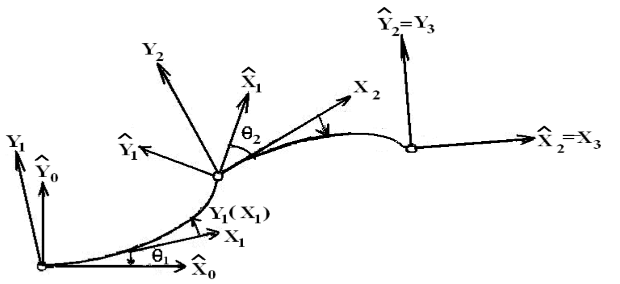

Figure 1. Two-link flexible manipulator.

The mathematical model has been developed by [27] using Lagrange and Assumed mode method. The links are modeled as Euler-Bernoulli beam with proper clamped-mass boundary conditions. Small elastic deflection assumption holds and it is restricted to the plane of rigid motion. The compact closed-form dynamic equation is given as:

$$B(q)\ddot{q} + h(q,\dot{q}) + K(q) = \tau \quad \text{......................... (1)}$$

$$q = f(\theta,\delta) \quad \text{... (2)}$$

Where θ is n-vector of joint coordinates and δ is m-vector of link deformation coordinates. Let N= n+m, then *q (θ, δ)* is N-vector characterising the arms configuration. *B* is a NxN positive definite symmetric inertial matrix, *h* is a N-vector containing Coriolis and centrifugal forces. *K* is a diagonal stiffness matrix. Detailed derivation of the mathematical model can be found in [27]

III. CONTROLLER DESIGN

The control schemes involve two stages. The first stage is the hybrid PD-PID controller design for the two-link flexible manipulator. In the second stage, the PD controller is extended to incorporate the adaptive scheme. To be able to estimate and compare the overall performance of the hybrid PD-PID controllers with and without adaptive scheme; performance index is calculated for the two control.

A. Hybrid PD-PID Controller Design

The PD-PID control structure [28] is shown in Fig 2. The PD controller ensures the hub follows the reference trajectory through angular error and joint velocity while the PID controller ensures the vibrations of the system are eliminated simultaneously through end-point acceleration feedback. The PD control input is given by:

$$u_{PD_i}(t) = A_{ci}\left(K_{Pi}(\theta_{id}(t) - \theta_i(t)) - K_{vi}\frac{d\theta_i}{dt}\right) \quad i=1,..(3)$$

Where u_{PDi} is PD control input, θ_{id}, *and* θi, A_{ci}, K_{Pi} and K_{vi} are desired hub angle, actual hub angle, and amplifier gain, proportional and derivative gains respectively.

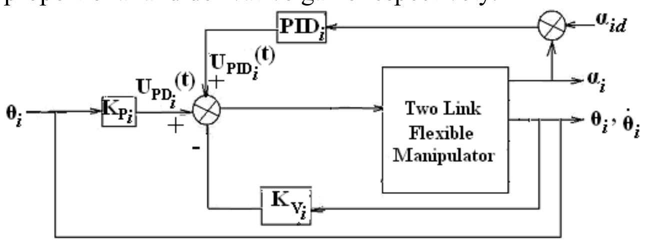

Fig. 2. PD-PID controller structure for the two-link planer flexible manipulator.

The PID controller uses end-point elastic acceleration for vibration suppression of each of the links because of the coupling effects. The control input is given as follows:

$$u_{PIDi}(t) = k_{Pi}e_i(t) + k_{Ii}\int e_i(t)dt + k_{Di}\frac{de_i}{dt} \quad i= 1, 2\text{......}(4)$$

Where u_{PIDi} is the PID controller input, K_{Pi}, K_{Ii}, and k_{vi} are the proportional, integral and derivative gains and e_i is given by:

$$e_i(t) = \alpha_{id}(t) - \alpha_i(t) \quad \text{.....................................(5)}$$

Where $\alpha_{id}(t)$ and $\alpha_i(t)$ are desired and actual end-point acceleration. $\alpha_{id}(t)$ is set to zero since the objective is to achieve zero end-point acceleration.

B. Adaptive Control Scheme

To be able to reject unanticipated disturbances on a dynamic system using conventional PD controller, there is need for continuous gain tuning of the controller gains. This work is inspired by continuous gain tuning as a way of solving the persistent problem of the most widely used industrial controller which makes tuning and retuning a part and parcel of the control process. This novel adaptive algorithm will not only reject structured and unstructured disturbances but it will also eliminate frequent tuning and retuning of the controller gains. The structure of the proposed adaptive controller is shown in Fig. 3. The algorithm is given by:

$$\begin{aligned} u_i(t) = \lambda_i(t)[k_{pi}(\theta_{id}(t) - \theta_i(t)) - k_{vi}\dot{\theta}_i(t)] \\ + [k_{Pi} + k_{Ii} + k_{Di}]e_i(t) \end{aligned} \quad i=1,2 \text{ .....(6)}$$

$$\lambda_i(t) = \frac{\Psi_i}{[\theta_{id}(t) - \theta_i(t)]^2 + 1} \quad i=12\text{..........................(7)}$$

Where u_i(t) is the total control input, λ_i(t) is the adaptive parameter that constantly adjust the PD controller gains, and ψ_i is the adaptive weight gain. Square of the tracking error is utilised to ensure the adaptive parameter is stable.

ISBN: 978-988-19252-4-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

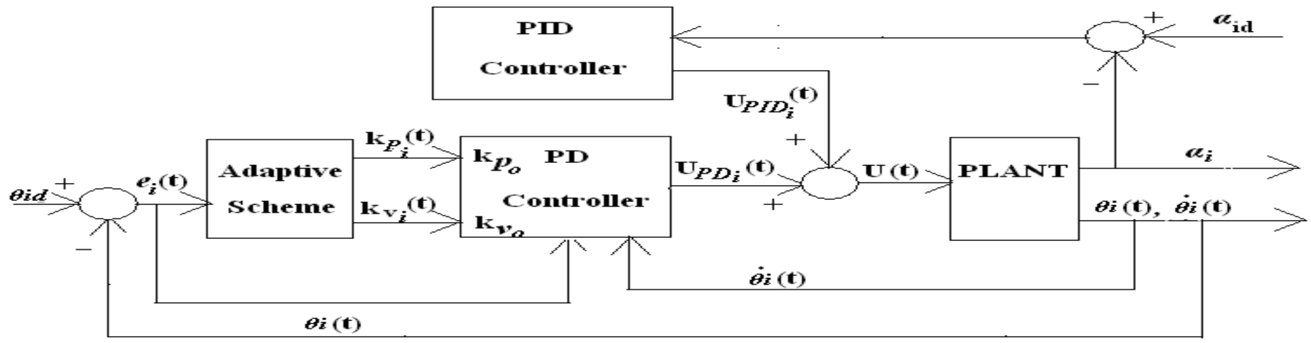

Fig. 3. The proposed hybrid direct adaptive PD-PID Control architecture.

C. Performance Index

The performance index J is given by:

$$J=\frac{1}{t_f}\int_0^{t_f}\left[\sum_{i=1}^{2}\left[\left(\frac{\theta_{id}-\theta_i}{\theta_{i\max}}\right)^2+\left(\frac{\dot\theta_{id}-\dot\theta_i}{\dot\theta_{i\max}}\right)^2+\left(\frac{\delta_{id}-\delta_i}{\delta_{i\max}}\right)^2+\left(\frac{\alpha_{id}-\alpha_i}{\alpha_{i\max}}\right)^2+\left(\frac{u_i}{u_{i\max}}\right)^2\right]\right]dt \quad ..(8)$$

Where: J is the performance index. t_f, θ_{imax}, θ_{imax}, δ_{imax}, α_{imax}, and τ_{imax} are the final simulation time, maximum hub angle, hub velocity, link deflection, tip acceleration and torque of link i respectively. θ_i, θ_i, δ_i, α_i, and u_i are the hub angle, hub velocity, link deflection, tip acceleration and controlled torque of link i respectively.

IV SIMULATION RESULTS

The proposed adaptive control scheme is tested through simulation in Matlab/Simulink environment and the results are presented. The parameters of the two-link flexible manipulator system are in table 1. The PD and PID gains of the feedback controller and the adaptive weight gain, after careful tuning, are presented in tables 2. To test the effectiveness of the proposed controller, the two link flexible manipulator was tested with two different input signals namely: a unit step input and a rectangular wave signal (see Fig.4). To study the robustness of the proposed controller two types of disturbances namely: white noise and sine wave (see Fig. 4) are introduced at first joint. The response obtained using hybrid PD-PID controller with adaptive scheme is compared with PD-PID controller without adaptation and the results are shown in Figures 5 to 10.

Table 1: Two-link flexible manipulator parameters [27]

Symbol	Parameter	Value
$\rho_1 = \rho_2$	Mass density	0.2 kgm^{-3}
$EI_1 = EI_2$	Flexural rigidity	1.0 Nm^2
$l_1 = l_1$	Length	0.5m
$Jh_1 = Jh_2$	Mass moment of inertia of the hub	0.1 kgm^2
G	Gear ratio	1
$M_1 = m_1$	Mass of the link	0.1kg
Mp	Mass of pay load	0.1kg
$J_{o1} = J_{o2}$	Mass moment of inertia of the link about its hub	0.0083 kgm^2
J_p	Mass moment of inertia of the end effector	0.0005 kgm^2

A. Effect of Unit Step Input on the Performance of the Proposed Controller

The hub angle tracking in Fig. 5a shows a smoother tracking without overshoot with the proposed controller compared to the PD-PID controller. The steady state error is reduced with the proposed controller compared to PD-PID controller (see Table 3). Figure 5b shows the end-points acceleration of the two controllers. It is observed that the amplitude of vibration is reduced, settles faster and also the steady state acceleration is reduced with the proposed controller compared to PD-PID controller (see Table 3). The total required energy is also reduced as seen in Fig. 5c with the applied torque and it settles down quickly with the proposed controller compared to the PD-PID. The overall performance index shows that the proposed controller has overall better performance compared to PD-PID controller.

Table 2: PD, PID and Adaptive gains

	PD gains		PID gains			Adaptive gain
	K_p	K_v	K_p	K_I	K_d	ψ
Link1	1.1	1.1	0.2	0.001	1.5	20
Link 2	0.25	0.42	0.1	0.1	0.5	1.2

Table 3: Comparing performances of direct adaptive hybrid PD-PID with hybrid PD-PID without adaptation

Response	PD-PID		Adaptive PD-PID	
	Link 1	Link 2.	Link 1.	Link 2.
End-point acceleration	0.3037	0.0074	0.2746	6.3×10^{-3}
Steady-state error	0.0009	0.0051	0.0008	0.0016
Maximum torque	0.9152	0.3722	1.0071	0.3344
Performance index	0.6484		0.6380	

B. Effect of White Noise Disturbance on Unit Step Input

To further demonstrate the effectiveness of the proposed controller white noise signal is introduced at the first joint and the results are shown in Fig. 6.

ISBN: 978-988-19252-4-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

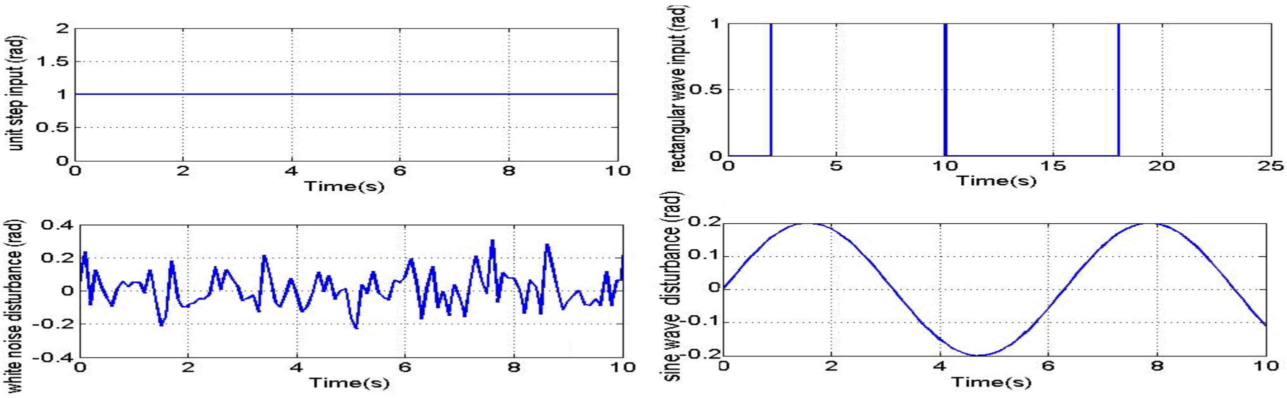

Figure 4 : Input and disturbance signals

It is observed that the white noise destabilises the PD-PID controller while there is no significant change in the proposed controller as shown in Fig. 6a, this shows the robustness of the proposed controller to an irregular disturbance like white noise. Similar result is observed in Figures 6b and 6c unstable behaviour was observed in acceleration and applied torque respectively with PD-PID controller. The proposed controller shows no change in its performances (Figures 6b and 6c).

C. Effect Of Sine Wave Disturbance on Unit Step Input

Effect of sine wave disturbance applied to the first joint on the proposed controller is studied. Figure 7a shows the tracking performance of the PD-PID controller which is unstable. On the other hand the proposed controller still maintains it performance and no significant change is observed. Figures 7b and 7c also show that the proposed controller is robust to the disturbance while the PD-PID has become highly of unstable.

D. Effect of Rectangular Wave Input Signal

Effect of changing the input signal from unit step input to rectangular wave signal is studied and the results are shown in Fig. 8a to 8c. A smooth tracking is observed for link 1 in the proposed controller but there is overshoot in the second link compared to the PD-PID controller that shows wavy tracking. Figure 8b shows that reduced acceleration is observed in the proposed controller. Higher applied torque is observed in link 1 with the proposed controller but lower torque in link 2. This can be explained because of very smooth tracking achieved in link 1 compared to PD-PID controller and also because of the coupling effect of the two-link flexible manipulator; the first link tracking has serious effect on the second link.

E. Effect of White Noise Disturbance on the Rectangular Wave Input

To truly establish the effectiveness of the proposed controller, white noise (Fig. 4) is introduced in the first joint and the observed results are presented in Fig. 9. The tracking shown in Fig. 9a further demonstrate the effectiveness if the proposed controller which shows no change in its performance compared to unstable behaviour observed for the PD-PID controller.

Figures 9b and 9c also show that the performance of the proposed controller remains unchanged in terms of end-point acceleration and applied torque respectively; while that of the PD-PID controller shows unstable behaviour and chattering in the applied torque.

F. Effect of Sine Wave Disturbance on the Rectangular Input

The sine wave disturbance was applied at first joint, it destabilises the PD-PID controller and the proposed controller remains unchanged. Figure 10a shows that the tracking of the proposed controller remains the same while unstable behaviour is observed with the PD-PID controller. the end-point acceleration in Fig. 10b and applied torque in Fig. 10c remain unchanged with the proposed controller whereas the performance not stable with PD-PID controller.

IV. CONCLUSSION

An adaptive hybrid PD-PID control algorithm has been developed for two-link flexible manipulator using a very simple adaptation law to constantly tune the PD gains. The proposed controller was tested through simulation in Matlab/Simulink environment. Extensive study was carried out on the proposed controller to show its effectiveness and robustness. Effect of changing input signal and noisy disturbance were comprehensively studied and results were presented and discussed. The performance of the proposed controller was compared with hybrid PD-PID controller to demonstrate its effectiveness. The results have demonstrated that a better performance is achieved with the proposed direct adaptive hybrid PD-PID controller compared to hybrid PD-PID controller without adaptation. Also the proposed controller is robust to changing input signal and noisy disturbance.

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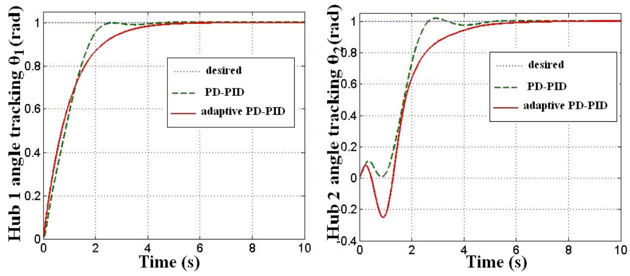

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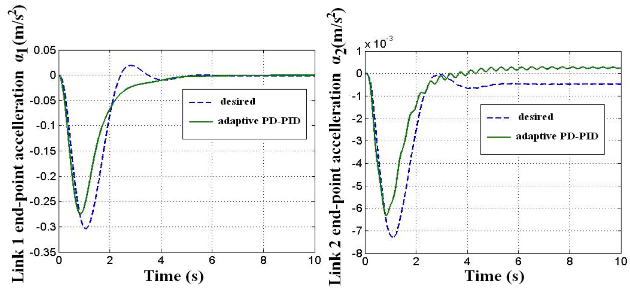

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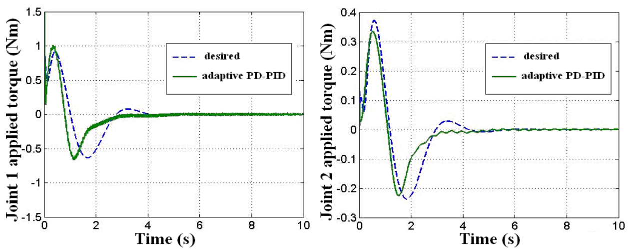

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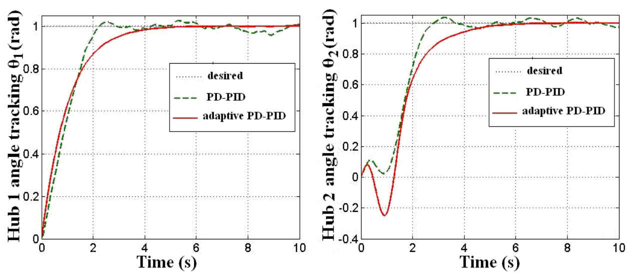
Figure 5: Time history with unit step response



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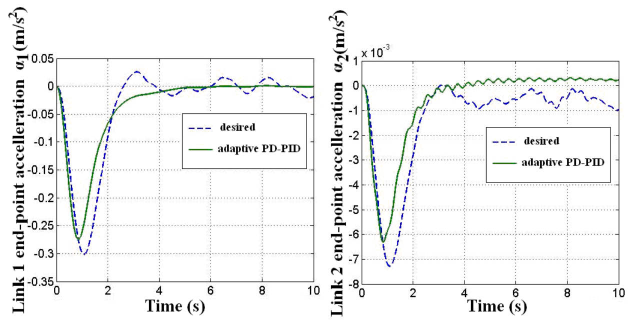

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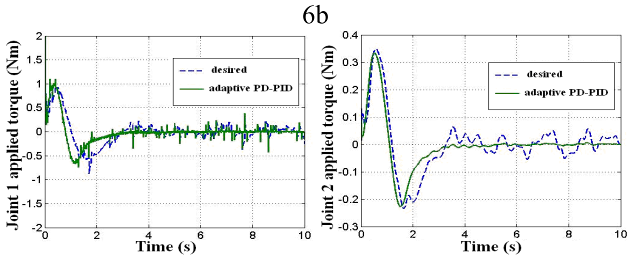

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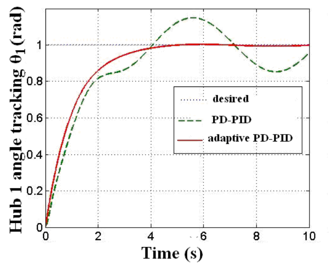
Figure 6: Time history of unit step input with white noise disturbance



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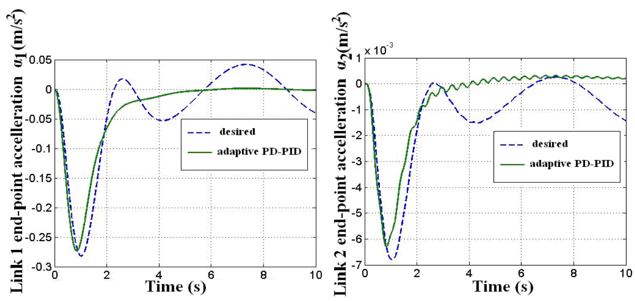

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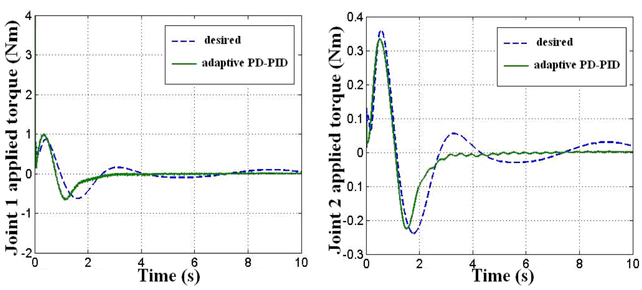

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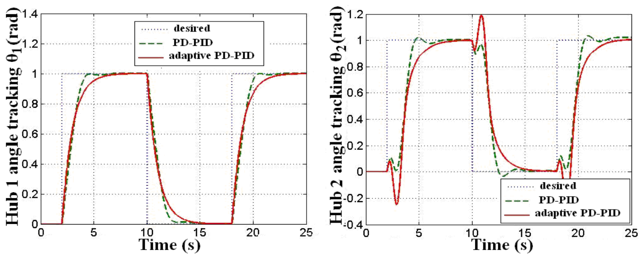
Figure 7: Time history of unit step input with sine wave Disturbance



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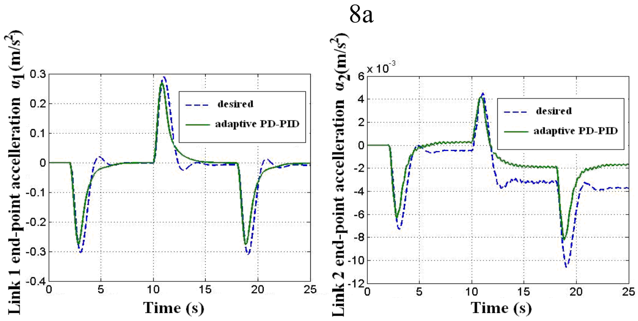

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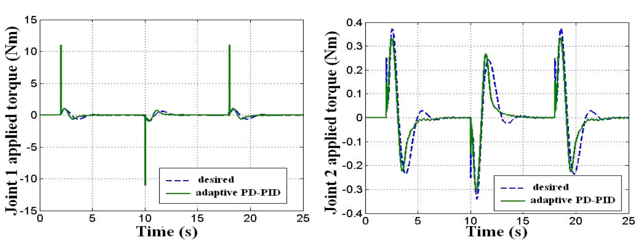

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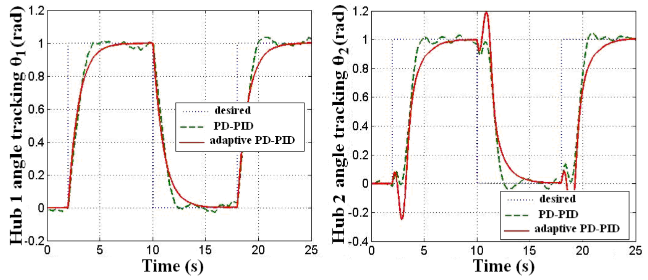
Figure 8: Time history of rectangular input.



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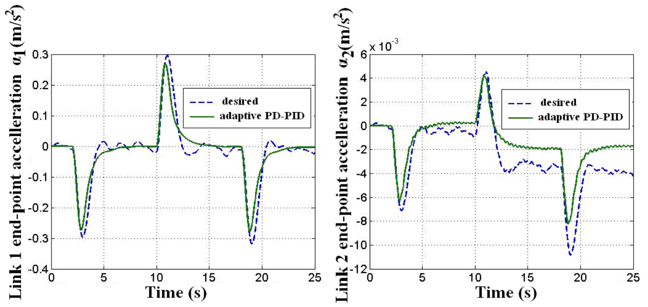

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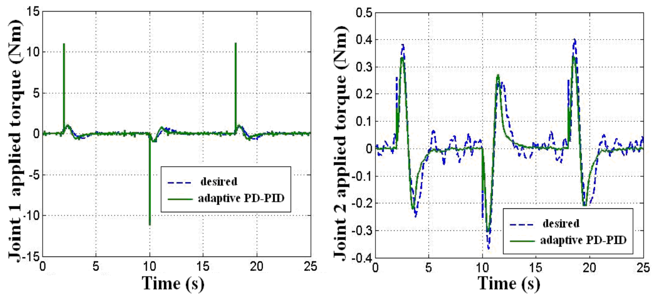

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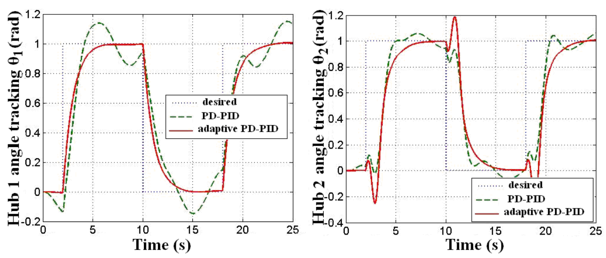
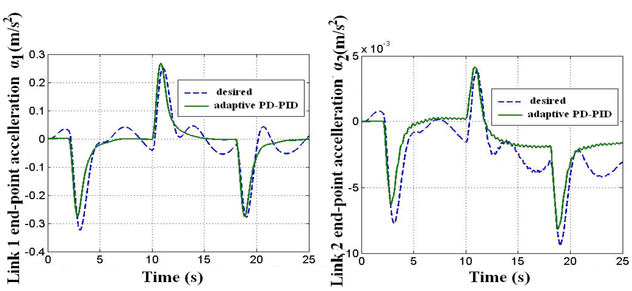
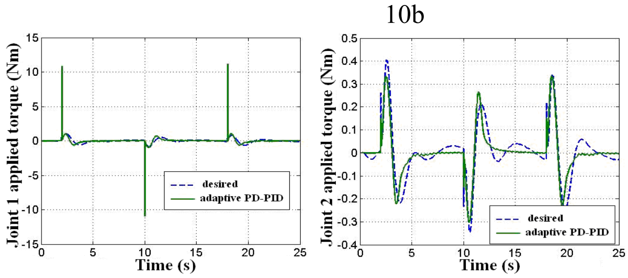
Figure 9: Time history of rectangular input with white noise disturbance



10a



10b



10c

Figure 10: Time history of rectangular input with sine wave disturbance