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Improving the Performance of Adaptive PDPID Control of Two-Link Flexible Robotic Manipulator with ILC

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***Abstract*— Flexible link manipulator systems (FLMs) have many advantages when compared to their rigid counterpart, these include: higher manipulations peed, low energy consumption, high payload to weight ratio and low overall cost. Controlling FLMs is challenging because of the highly distributed nature of the system. This paper presents a very simple and efficient control algorithm using adaptive Proportional Derivative (PD) Proportional Integral Derivative (PID) (traditional controller) and Iterative Learning Control (ILC) for two-link flexible manipulator. The adaptive control scheme constantly tunes the PD control gains, the PID controls the vibration and the ILC improves the overall performance of the system. The manipulator was modeled using Lagrange and assume mode method. The proposed control law was tested in Matlab/Simulink simulation environment. The performance and the performance index of the proposed control law were compared with those of the PDPID, PDPIDILC and adaptive PDPID controllers. The robustness of the proposed control law was further demonstrated through studying the effect of constant, repeating sequence, square wave and white noise disturbances. The result show that the proposed control law is robust to all these disturbances and has the best performance in all the cases studied.**

***Index Terms*— Adaptive controls, flexible link manipulator systems, PD Control, ILC scheme, PID control**

I. INTRODUCTION

To remain competitive in today's industry, high productivity and low cost of production are key amongst other things. The use of robot in manufacturing was phenomena as most robots are used to achieve work in the most hazardous environments where men may not survive, is one of the numerous advantages of robots. The traditional robots were made rigid and are very heavy, they consume more power and they are slow in operation [1], they have low payload to weight ratio because large payload cause them to sag [2], and so on . To overcome some of these problems, flexible link manipulators were developed which are lighter in weight, consume less power, have faster manipulation, higher payload to weight ratio, require less material etc [3]. With all these advantages, to control such a flexible system comes with a lot of difficulties because of the high distributed nature of such a system [4]. Proportional Integral Derivative (PID) Controller constitutes over 90% of industrial controller in use today [6]. Advantages of PID controller include: they have simple structure, they are easy to implement, they are robust over a wide operation range and they are cheap [7]. That was why a lot of PID based controller has been used in the literature [5-8].

There are two types of PID controllers namely: fixed gain PID controller, and variable gain PID controller. The performance of the fixed gain controller is limited in real time operation because there will always be a steady state error due to the dynamic nature of the real time operation environment. Variable gains PID controllers are achieved through some form of adaptation which tunes the gains as required. These tuning algorithm are referred to as adaptive control scheme. A number of adaptive control algorithms have been implemented in the literature [9-11] to improve the performance of the fixed gain PID controllers. The major drawback of most of these adaptive controllers is that they require a high computational load [12] that makes them to be slower in operation. Another control scheme that is used to improve the performance of PID controllers in the literature is the Iterative learning control.

Iterative Learning Control (ILC) is a feedforward controller that is used to improve the performance of any system carrying out repetitive tasks by reducing the tracking error from one trial to the next iteratively [13]. ILC schemes estimates compensation from the previous input and error values for the next iteration with the aim of reducing and converging these error. It has been reported in the literature that a properly designed feedforward controller reduces the complexity of the feedback controller [14]. The feedback controller ensures the stability of the whole system [15] while the ILC will improve the overall performance of the system [6].

In this study, a simple and efficient iterative learning scheme was developed in combination with adaptive PDPID controller to achieve an improved overall performance of the system. These control schemes was implemented for two-link flexible manipulator in set-point regulation task. The links of the manipulator was modeled by De Luca and Siciliano [16] using Lagrange and assumed mode method. The performance of the proposed control scheme was studied through simulation in Matlab/Simulink simulation environment. The performance and the performance index of the proposed control law were compared with those of the PDPID, PDPIDILC and adaptive PDPID controllers. The results are presented and fully discussed. The paper ends in concluding remarks.

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II. MATHEMATICAL MODELLING

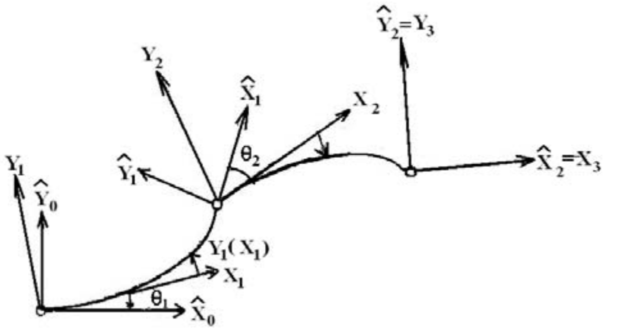


Figure 1. Two-link flexible manipulator.

The mathematical model used in this study was developed by [16] using Lagrange and Assumed mode method. The links were modeled as Euler-Bernoulli beam with proper clamped-mass boundary conditions. It assumes small elastic deflection and it is restricted to the plane of rigid motion. The compact closed-form of the dynamic equation is given as:

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

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

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. Readers can consult [16] for the detailed derivation of the mathematical model.

III. CONTROLLER DESIGN

The control schemes involve four stages. The first stage is the hybrid PD-PID controller design for the two-link flexible manipulator. The second stage involves incorporation of ILC control schemes. In the third stage the ILC controller was removed and the PD controller was extended to incorporate the adaptive scheme. This was done to be able to compare the performance of all these controllers. The final stage, ILC control scheme was incorporated to the adaptive PDPID. The performance index was calculated for all the four controllers.

A. PD-PID Controller Design

The PD-PID control structure was developed for two-link flexible manipulator in [17] as shown in Figure 2. The PD controller ensures the hub follows the reference trajectory using angular error and joint velocity in the feedback loop 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:

$$u_{PD_i}(t) = A_{ci}\left(K_{Pi}(\theta_{id}(t) - \theta_i(t)) - K_{vi}\frac{d\theta_i}{dt} \right) \quad =1,2 \qquad (3)$$

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

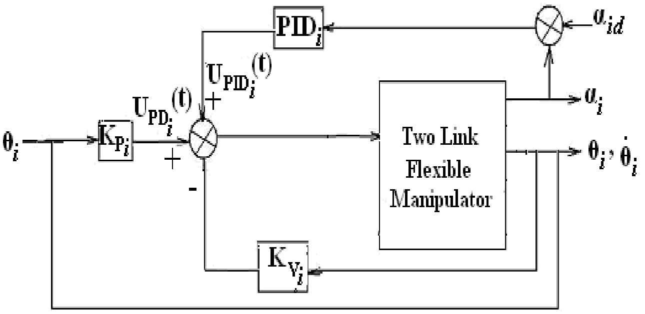


Fig. 2. PD-PID controller structure for the two-link planer flexible manipulator

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

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

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

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

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. The detail of the control schemes can be found in [17]

B. Iterative Learning Control Scheme

ILC is used to improve the performance of the PD-PID controller in A above. The PDPID control scheme was extended to include ILC. The structure of the control law is shown in Fig.3 according to [6].

The structure of the iterative learning scheme is shown in Fig. 4. and is given by:

$$u_{i(k+1)}(t) = \Gamma_i(\tau_{ik}(t) + \tau_{i(k+1)}(t)) + \Psi_i e_{ik}^2(t) \quad \text{i=1,2} \quad (6)$$

Where ui (k+1) and τik are the next iteration and present total control inputs respectively, Γi is the learning filter, and ψi is the Proportional learning gain.

C. Adaptive Control Scheme

Figure 5. shows the adaptive PDPID control structure according to [18]. The adaptive control scheme is given by:

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

Where λi(t) is the adaptive parameter that constantly adjusts the PD controller gains, and Φi is the adaptive weight gain.

D. Adaptive PDPID with ILC Control Scheme

The proposed control architecture is shown in Fig. 6. achieved by extending controller in subsection C to incorporate the ILC in fig.4. the total control input according to [19] is given by

$$
\begin{aligned}
u_i(t) = \lambda_i(t)(\theta_{id}(t) - \theta_i(t) + u_{i(k+1)}) & \\
[k_{pi}(\theta_{id}(t) - \theta_i(t)) - k_{vi}\dot{\theta}_i(t)] & \text{ ; i=1,} \quad (8) \\
+ [k_{Pi} + k_{Ii} + k_{Di}]e_i(t) &
\end{aligned}
$$

E. Performance Index

The performance index J is calculated by the equations below:

$$
J = \frac{1}{t_f}\int_0^{t_f}\left[\sum_{i=1}^{2}\left[\begin{array}{l}\left(\frac{\theta_{id}-\theta_i}{\theta_{i\max}}\right)^2 + \left(\frac{\dot{\theta}_{id}-\dot{\theta}_i}{\dot{\theta}_{i\max}}\right)^2 + \left(\frac{\delta_{id}-\delta_i}{\delta_{i\max}}\right)^2 \\ + \left(\frac{\alpha_{id}-\alpha_i}{\alpha_{i\max}}\right)^2 + \left(\frac{u_i}{u_{i\max}}\right)^2\end{array}\right]\right]dt \quad (9)
$$

Where: J is the performance index. t_f, θ_{imax}, θ_{imax}, $\delta_{imax,}$ α_{imax}, and τ_{imax} are the final simulation time, maximum hub angle, hub velocity, link deflection, tip acceleration and torque of link respectively. θi, θi, δi, αi, and ui are the hub angle, hub velocity, link deflection, tip acceleration and controlled torque of link respectively.

IV SIMULATION RESULTS

The proposed control scheme was tested through simulation in Matlab/Simulink environment. The robustness of the proposed controller was tested with constant disturbance, repeated sequence disturbance, square wave disturbance and white noise disturbance. The performance indexes of the four controllers were also compared and the results are presented. The parameters used for the two-link flexible manipulator system are presented in Table 1. The PD and PID gains of the feedback controller, the adaptive weight gain, and the ILC gain, after careful tuning, are presented in Tables 2. The system was excited with a step input of 60 degree, the hub tracking, tracking error, end-point acceleration and applied torque for the four controllers are shown in Figure 7. The hub angle tracking with the proposed controller was faster (see Figure 7a) as compared with the adaptive PDPID, PDPIDILC and PDPID controllers. The proposed controller also has the least steady state error (see Figure 7b). The proposed controller has the least amplitude of vibration when compared to the other three controllers and it settles down quickly (see Figure 7c). The overall torque used with the proposed controller is lower when compared to the PDPID, PDPIDILC and PDPID controllers (see Figure 7d). 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.

Effect of constant disturbance, repeated sequence disturbance (see Figure 8 a), square wave disturbance for links 1and 2 are shown in Figure 8b and 8b respectively, and white noise disturbance (see Figure 8d) were studied below.

Table 1: Two-link flexible manipulator parameters

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 constant Disturbance

The constant disturbances ware introduced at the first joint and the results are shown in Figure 9. It was observed that the constant disturbance degraded the tracking of the PDPID and PDPIDILC controllers while there was no significant change in the performances of the adaptive PDPID controller but the proposed controller shows the best performance of all as shown in Fig. 9a. the proposed controller also shows the least tracking error as shown in Figure 9b. Figures 9c and 9d show the end-point acceleration and the applied torque. The proposed controller has the minimum end-point acceleration and torque over the other three controllers.

B. Effect Of Repeating Sequence Disturbance

Repeating sequence disturbance signal was introduced to the two links and the results are shown in Figure 10. The hub tracking (see Figure 10a) of the proposed controller gives the best performance over the rest controller. The similar Behaviour is seen in Figures 10b, 10c and 10d. the proposed controller has the least tracking error the least amplitude of vibration and the first to settle down as compared to the rest controllers. Minimum torque is also used up by the proposed controller.

C. Effect of Square Wave Disturbance

Two different square waves were applied at each of the both joints as shown in the Figures 8b and 8c and the results are shown in Figure 11. An unstable tracking performance of PDPID and PDPIDILC controllers were seen in Figure 11a with no significant change in the Behaviour of the adaptive PDPID and the proposed controller. With the proposed controller having overall best tracking performance. Figures 11b to 11d also show that the proposed controller is robust to the square wave disturbances as the proposed controller has the least tracking error, the least amplitude of vibration and overall minimum torque. This shows the robustness of the proposed controller.

Table 2: PD, PID, adaptive weight and ILC gains

Links	Ac	PD gains		PID gains			Adaptive Weight gain	ILC gains	
		Kp	Kv	Kp	K_I	Kd	Φ	Γ	Ψ
Link1	1	1.1	1.1	0.2	0.001	1.5	17.5	0.0005	0.15
Link 2	1	0.25	0.42	0.1	0.1	0.5	1.42	0.0001	0.15

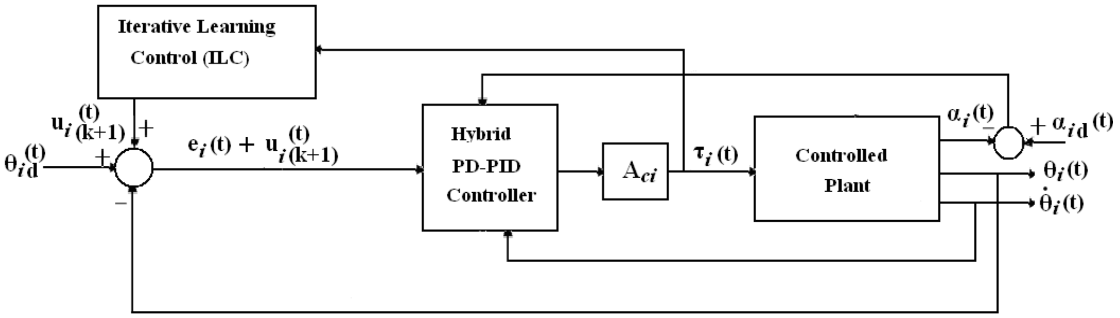


Fig. 3. PDPIDILC Control architecture [6]

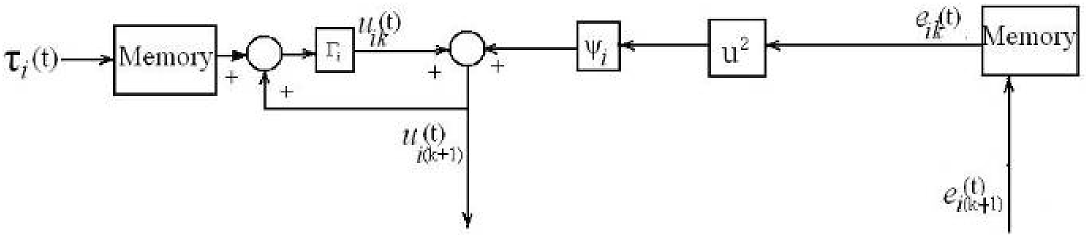


Fig. 4. Structure of the ILC learning algorithm.

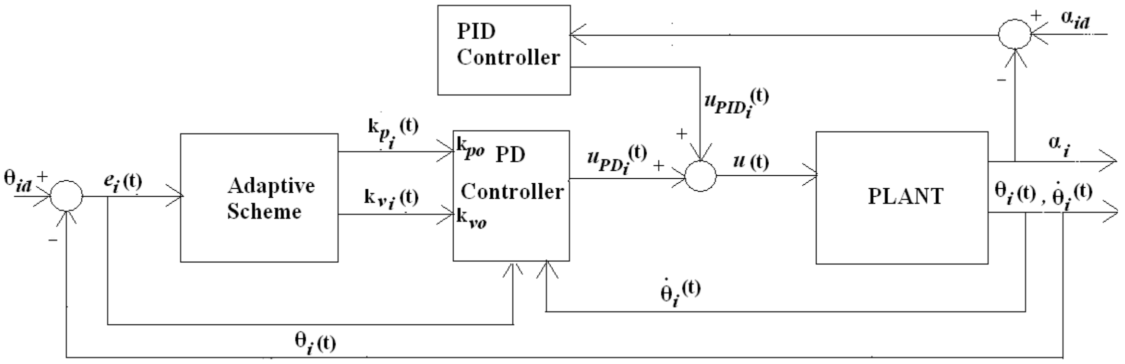


Figure 5. Structure of the Adaptive PDPID Control [18]

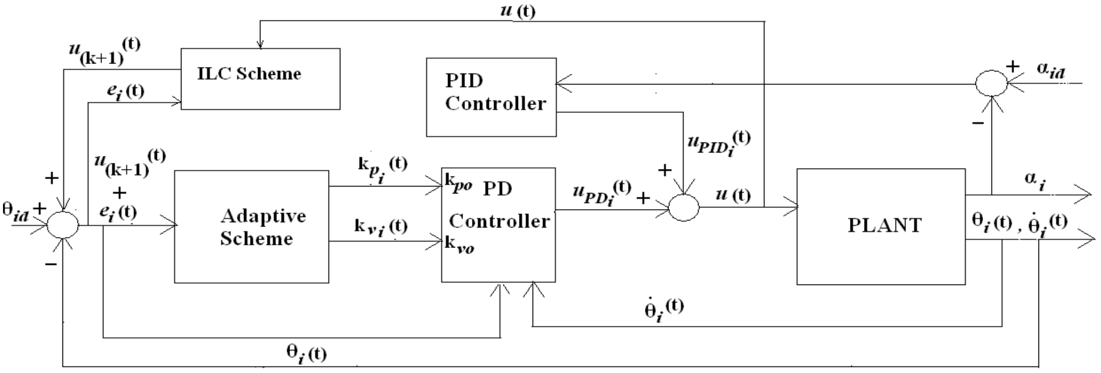


Figure 6. The adaptive PDPILILC control architecture

D. *Effect of White Noise Disturbance*

To further demonstrate the robustness of the proposed controller a white noise signal was introduced at each linkand the results are shown in Fig. 12. It was observed that the white noise destabilizes the PDPID and PDPIDILC controllers while there were no significant changes in the performance of the adaptive PDPID controller and proposed controller (see Figure 12a). The proposed controller has the overall best performance. Similar results were observed in Fig. 12b to 12d. Large steady state errors were seen from the PDPID and PDPIDILC controllers (see Figure 12b). Unstable Behaviour in acceleration and applied torque (see Figure 12c and 10d respectively) with PDPID and PDPIDILC controllers. Though adaptive PDPID and the proposed controller show no significant changes in their behaviors but the proposed controller still maintain its overall best performance. This shows the robustness of the proposed controller to an irregular disturbance like white noise.

E. *Performance Index*

The results of the performance index study are presented in Table 3 using equation 9. These results were generated simultaneously during the controllers testing simulation in Matlab/Simulink. Figure 13 shows the bar chat of the performance indexes of the four controllers. The least performed controller is the PDPID controller closely followed by PDPIDILC controller. This is expected as the function of ILC is to improve performance which clearly improves the performance of the PDPID in the PDPIDILC controller. The best performance is seen in the proposed controller as it is seen to have further improved the adaptive PDPID controller. It is only the proposed controller that performs above 50% in all the cases; this has further proved the effectiveness and robustness of the proposed control law.

IV. CONCLUSSION

In this paper, the performance of an adaptive control scheme has been improved using iterative learning control schemes. The control law has been implemented and tested for a two-link flexible manipulator in Matlab/Simulink simulation environment. The PD controller ensures that the hub angle tracking, the PID ensures the vibration suppression, the adaptive scheme constantly tunes the PD gains to be able to cope with unforeseen disturbances and the ILC improves the overall performance of the system. The Iterative learning control scheme uses the previous control input and the tracking error to provide a compensation for the next trial thereby ensuring reduction of error and error convergence from one iteration to the next. The proposed control law was compared with PDPID, PDPIDILC and adaptive PDPID controllers. The performance of the proposed control law was also studied with constant, repeating sequence, square wave and white noise disturbances, the proposed control has the overall best performance. To further demonstrate the effectiveness of the proposed control law, the performance indexes of all the controllers were studied without and with various disturbances, the results prove that the proposed controller has the best performance index in all the cases studied. It can be concluded that the proposed control law is robust to constant, repeating sequence, square wave and white noise disturbances.

REFERENCES

[1] M.S. Alam, and M.O Tokhi, Hybrid Fuzzy logic control with genetic optimization for a single link flexible manipulator, Journal of Engineering Applications of Artificial intelligence, vol. 2, 2008, pp. 858- 873,

[2] T. Zebin, Modeling and Control of a Two-link Flexible Manipulator using Fuzzy Logic and Genetic Optimization Techniques, Journal Of Computers, Vol. 7, No. 3, 2012, pp. 578- 585.

[3] J. G. Yim, J. S.Yeon, J. Lee, J. H. Park, S. H. Lee, and J. S. Hur, Robust control of flexible robot manipulators, Proceedings of the SICEICASE International Joint Conference, 2006, pp. 3963 – 3968.

[4] S.K. Dwivedy, and P. Eberhard, Dynamic analysis of flexible manipulators, a literature review, Mechanism and Machine Theory, (2006), vol. 41, no. 7, pp. 749-777.

[5] R. Matousek, P. Minar, S. Lang, and M. Seda HC12: Efficient PID Controller Design, Engineering Letters, vol. 20(1), 2012, pp. 42-48

[6] R. M. Mahamood and J. O. Pedro, Hybrid PD-PID with Iterative Learning Control for Two-Link Flexible Manipulator, Lecture note in Engineering and Computer Science , Proceedings of the World Congress on Engineering and Computer Science 2011 vol. II WCECS 2011, October 19-21, 2011, San Francisco, USA, pp. 966-971

[7] K. H. Ang, G. Chong, and Y. Li, PID control system analysis, design, and technology, IEEE Transactions on Control Systems Technology, Vol. 13, No. 4, 2005, pp. 559 – 576.

[8] A. N. A.l-Rabadi and M. A. Barghash, Fuzzy-PID Control via Genetic Algorithm-Based Settings for the Intelligent DC-to-DC Step-Down Buck Regulation, Engineering Letters, vol. 20(2), 2012, pp. 176-195

[9] U. Onen, M Kalyoncu., M. Tinkir, and F. M. Botsali, Adaptive network based fuzzy logic control of a rigid – flexible robot manipulator, International Conference on Computer and Automation Engineering (ICCAE), vol. 1, 2010, pp102-106.

[10] M. A. Ahmad, R.M.T.J. Ismail, and M. S. Ramli, “Optimal Control With Input Shaping for Input Tracking and Vibration Suppression of a Flexible Joint manipulator”, European Journal of Scientific Research, 2009, Vol. 28(4), pp.583-599.

[11] J. Becedas, J. R. Trapero, V. Feliu, and H. Sira-Ramírez, Adaptive controller for single-link flexible manipulators based on algebraic identification and generalized proportional integral control, IEEE Transactions on Systems, Man, And Cybernetics— Part B: Cybernetics, vol. 39, no. 3, June 2009, pp. 735-751.

[12] T. –Y. Kuc, K. Nam, and J.S. Lee, An iterative learning control of robot manipulator, IEEE Transaction on Robotic and Automation, 1991, vol.7 (6), pp. 835-842.

[13] D. H. Owens, and S. Daley, Iterative learning control- amonotonic and optimization, Int. J. Appl. Math. Comput. Sci., Vol. 18, no. 3, 2008, pp. 279–293.

[14] M. O. Tohki, and M. Z. Md. Zain, Hybrid learning control schemes with acceleration feedback of a flexible manipulator system, Proceedings of IMechE Part J. Journal of System and Control Engineering, vol. 220, 2006, pp. 257-267.

[15] A. De Luca, and B. Sciciliano, An asymptotically stable joint PD controller for robot with flexible link under gravity, 31st IEEE Conference on Decision and Control, Tucson, AZ, 1992, pp.325-318.

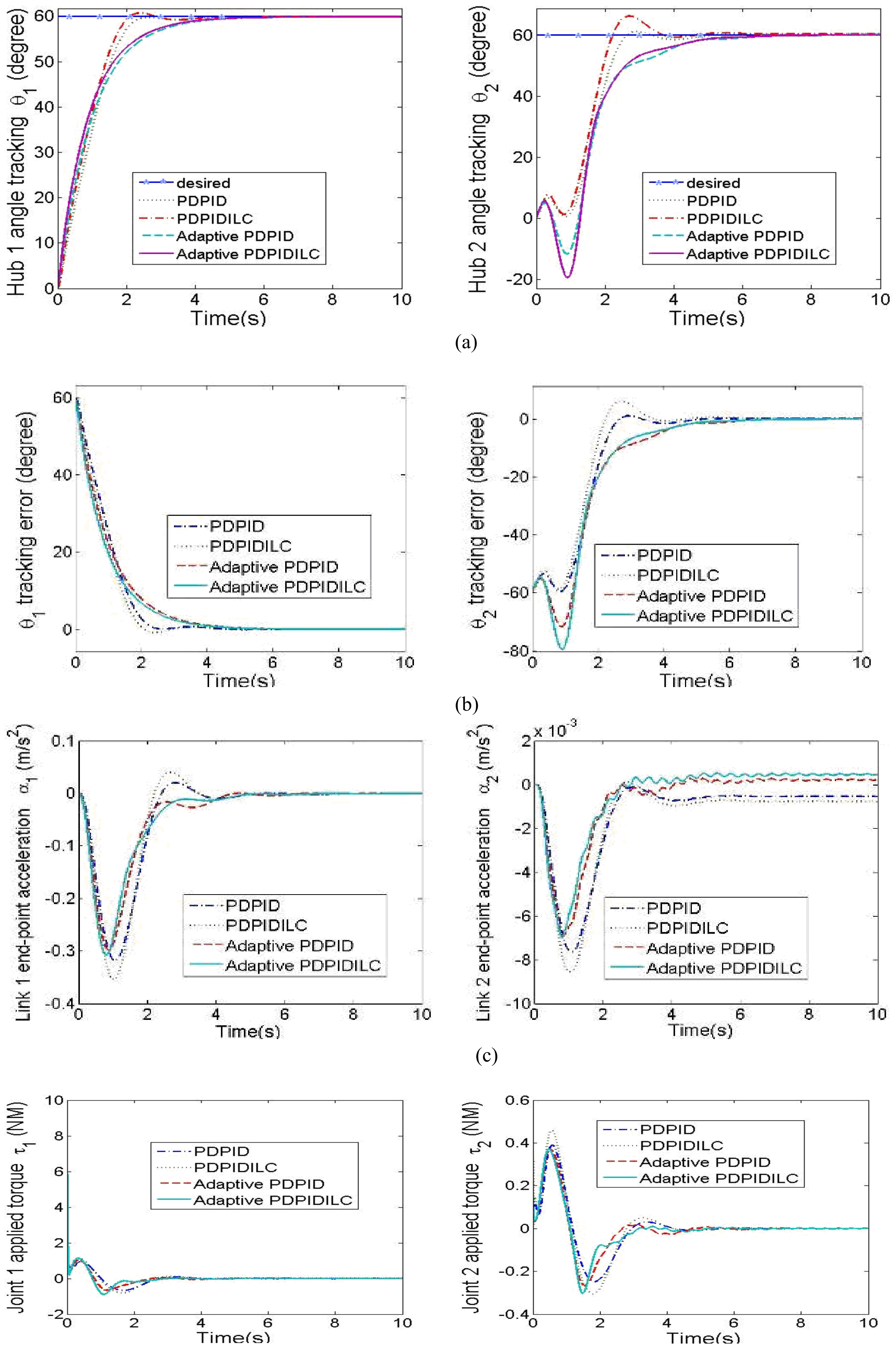
[16] A. De Luca, and B. Sciciliano, closed-form dynamic model of planar multilink lightweight robots, IEEE Transactions on Systems, Man and Cybernetics, Vol. 21, No. 4, 1991, pp. 826 – 839.

[17] M. R. Mahamood, and J. O. Pedro, (2011), “Hybrid PD/PID Controller Design for Two-Link Flexible Manipulators”, Proceedings of the 8th Asian Control Conference (ASCC), Kaohsiung, Taiwan, pp. 1358-1363.

[18] R. M. Mahamood, Direct Adaptive Hybrid PD-PID Controller for Two-Link Flexible Robotic Manipulator, WCECS 2012, Accepted.

[19] R. M. Mahamood, Adaptive PDPID with Iterative Learning for Two-link Flexible Manipulator, Lecture Notes in Engineering and

Computer Science: Proceedings of The World Congress on Engineering 2012, WCE 2012, 4-6 July, 2012, London, U.K., vol. 3, pp. 1710-1715



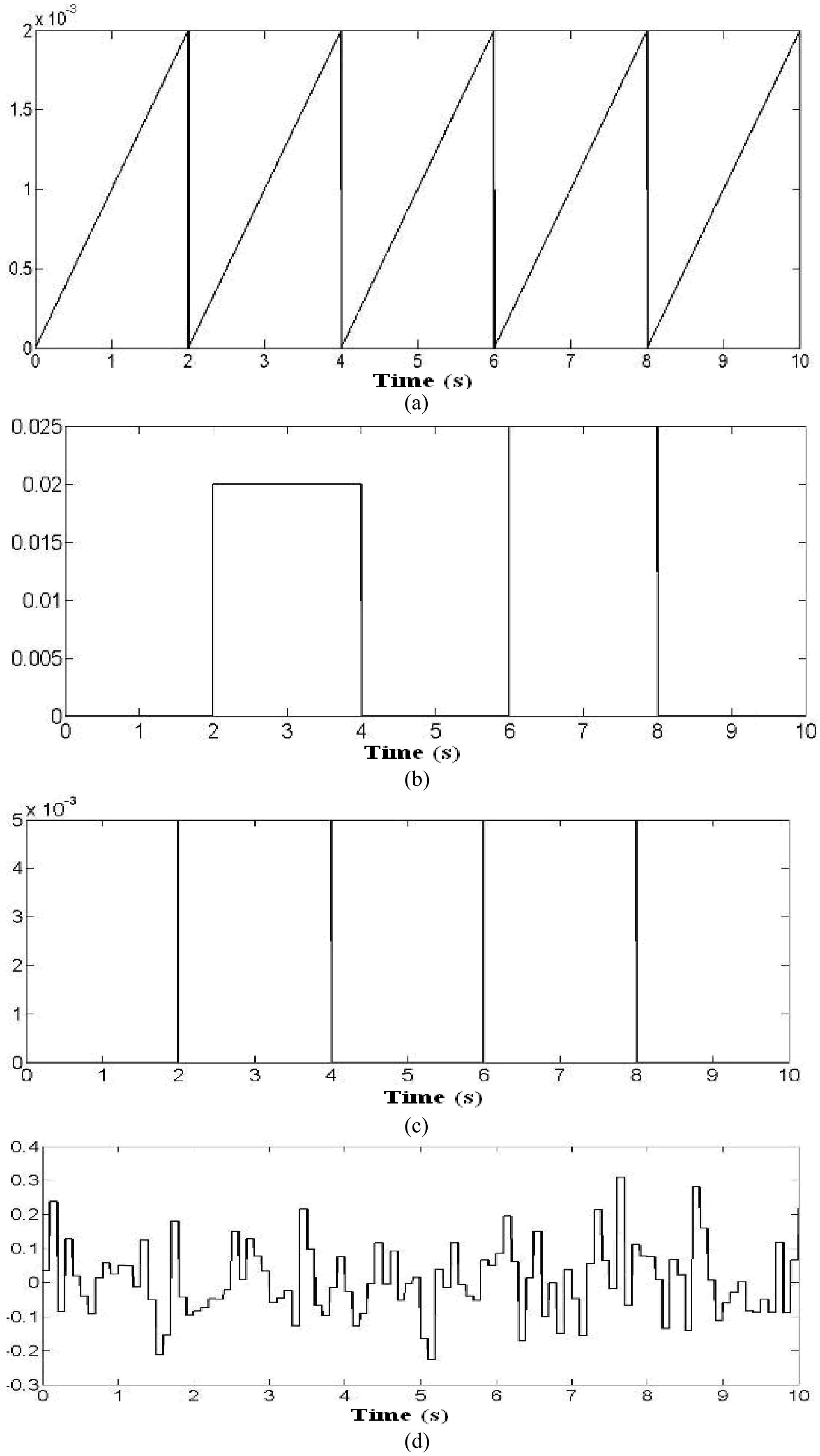
(a)

(b)

(c)

(d)

Figure 7: Time history of (a) hub angle tracking, (b)tracking error, (c) end-point acceleration and (d) applied torque with 60 degree step input



(a)

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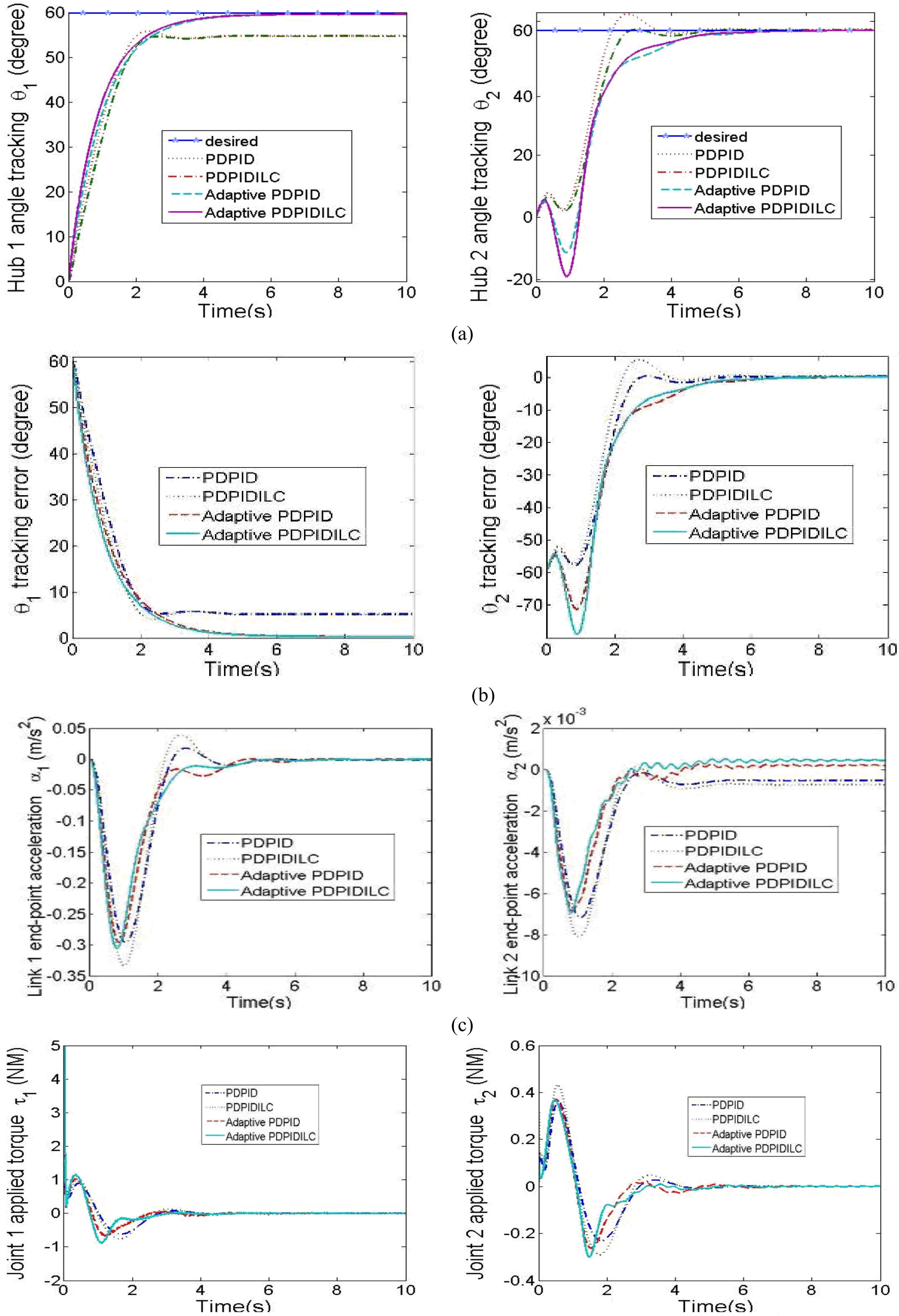
Figure 8 : Disturbance signals, (a) repeating sequence, (b) and (c) Square wave for link 1 and link 2 respectively (d) White noise



(a)

(b)

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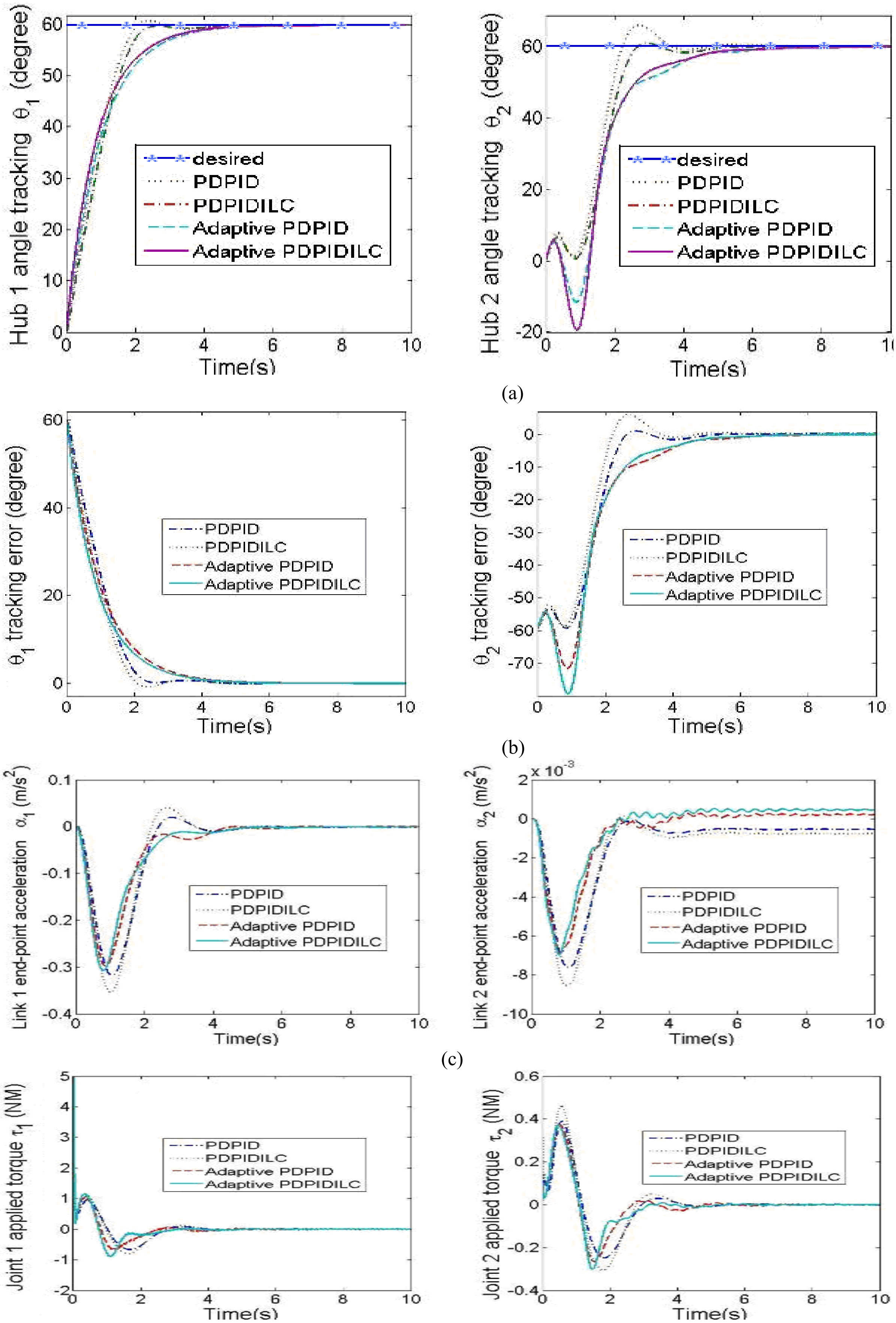
Figure 9: Time history of (a) hub angle tracking, (b)tracking error, (c) end-point acceleration and (d) applied torque with constant disturbance



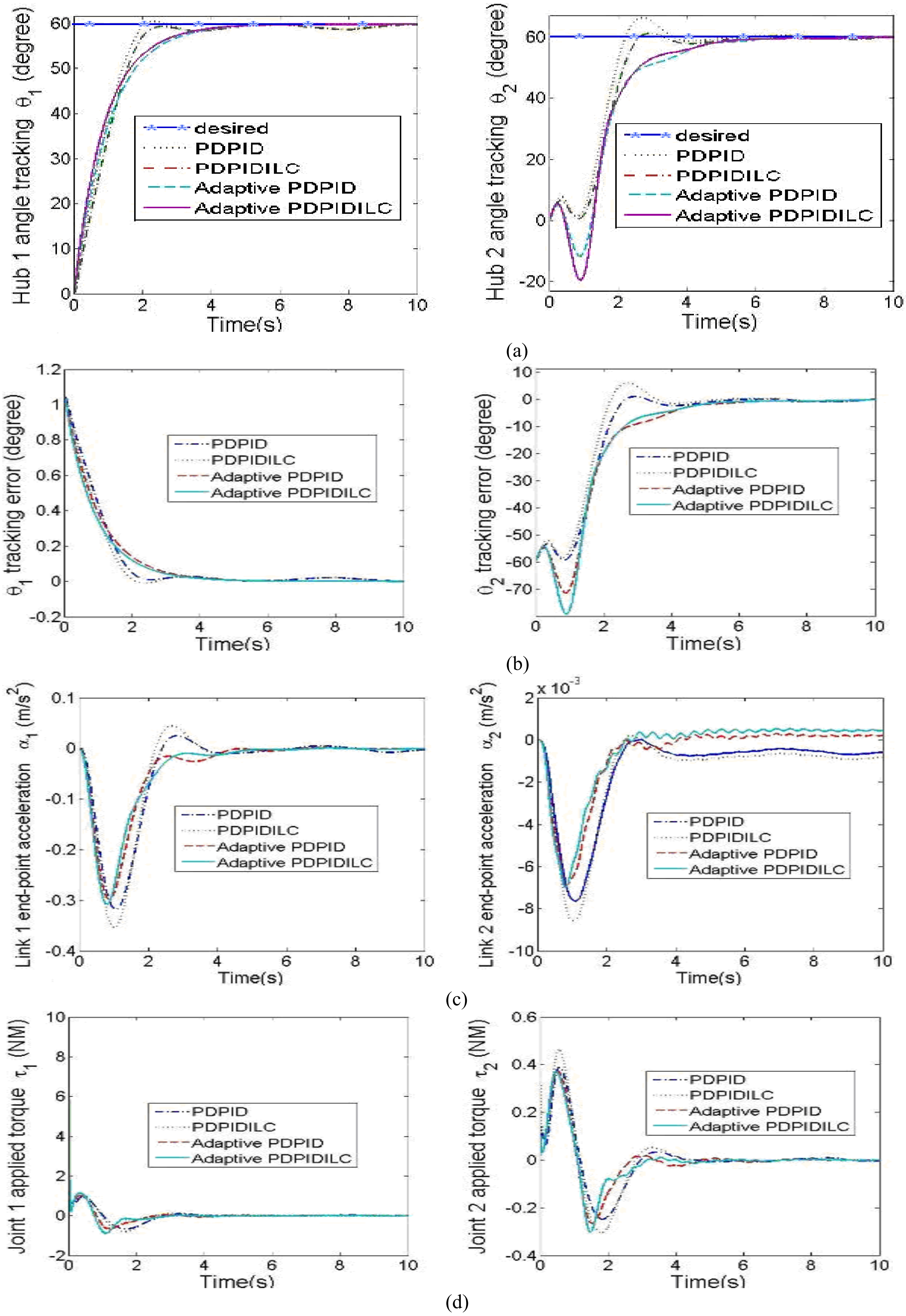
(a)

(b)

(c)

(d)

Figure 10: Time history of (a) hub angle tracking, (b)tracking error, (c) end-point acceleration and (d) applied torque with repeating sequence disturbance



(a)

(b)

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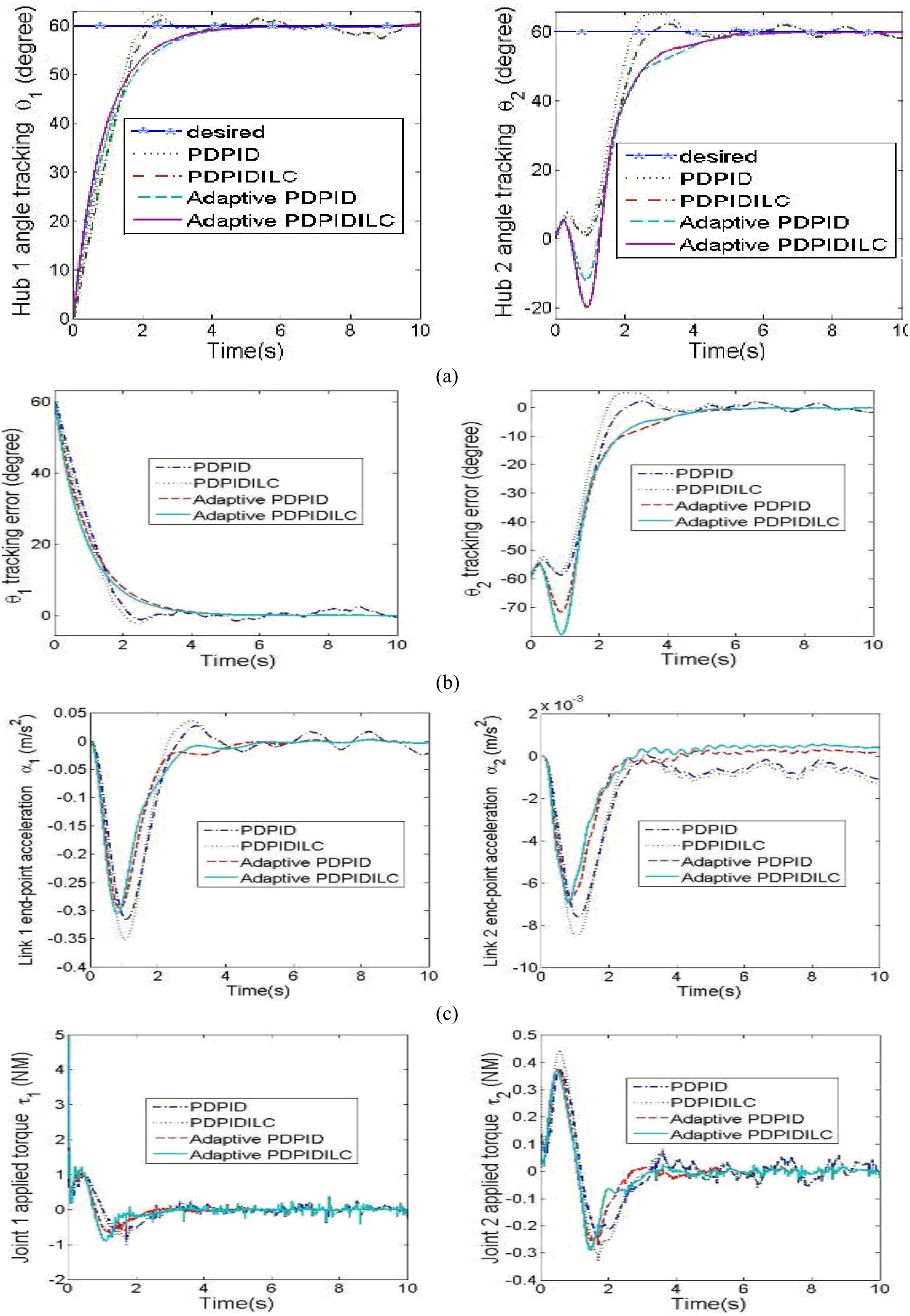
Figure 11: Time history of (a) hub angle tracking, (b)tracking error, (c) end-point acceleration and (d) applied torque with square wave disturbance



(a)

(b)

(c)

(d)

Figure 12: Time history of (a) hub angle tracking, (b)tracking error, (c) end-point acceleration and (d) applied torque with white noise disturbance

Table 3: Performance Index

Controller	With Step input	With white noise disturbance	With repeating sequence disturbance	With square wave disturbance	With constant disturbance
PDPID	0.3991	0.3913	0.3794	0.3793	0.3665
PDPIDILC	0.4357	0.4327	0.4259	0.4255	0.4089
Adaptive PDPID	0.4776	0.4650	0.4683	0.4679	0.4642
Adaptive PDPIDILC	0.5698	0.5573	0.5607	0.5602	0.5544