Design of Adaptive Preview Control

Nidhika Birla, Akhilesh Swarup

Department of Electrical Engineering, National Institute of Technology, Kurukshetra, INDIA
(e-mail: {nidhikabirla, akhilesh.swarup}@gmail.com).

Abstract: This paper presents the formulation of Adaptive Preview Control (APC) for discrete-time systems. The Adaptive Preview Control scheme includes a combination of Adaptive Control and Preview Control and thus, gains the advantage of both the schemes. This scheme enhances the transient behaviour by adapting to the real-time previewed signals of the system. The Adaptive Gain update Law is designed using Lyapunov Function and thus, the asymptotic stability of the closed-loop system is guaranteed. The proposed APC design is tested for two benchmark control problems using MATLAB platform. The results validate that the performance of the system enhances by the use of Adaptive Preview Control structure in terms of transient characteristics.

Keywords: Adaptive Preview Control, Discrete Time System, Preview Control, Lyapunov Function.

1. INTRODUCTION

The term Preview Control is generally associated with a particular category of anticipative control problems with a preview horizon that extends for a fixed time into the future. The field of Preview Control is concerned with using the advance knowledge of disturbances or references to improve the tracking quality or disturbance rejection. If the future information of references or disturbances is accessible, then the performance of transient responses can be improved substantially. This type of control problem that utilizes the future information on the reference signal and/or disturbances is called Preview Control Problem. The Preview Control problem, in simple terms, is an optimization problem, where the best value of the controller is to be determined. This makes the Preview Control problem compatible and solvable through the standard optimization and controller design theories.

The solution of Preview Control problem can be obtained using classical, as well as, modern approaches that minimize evaluation function through all period of time. The classical approaches presented by (Tomizuka 1975; Kadakkal et al. 2008; Tsuchiya et al. 1988; Negm et al. 1991, 2006; Egami et al. 1995; Moran et al. 1996; Kojima et al. 1997, 1998, 1999, 2003, 2006; Takaba 1998, 2000, 2003; Mianzo et al. 1998, 2007; Tian 2002; Tadmor et al. 2003a, b; Hazawa et al. 2004; Kanzaki et al. 2005; Farooq et al. 2005; Yokoyama et al. 2009; Yan et al. 2009; Silvestre et al. 2009; Liao et al. 2009; Akbari et al. 2010; Sumer et al. 2010; Kristalny et al. 2010; Yim 2011; Wang et al. 2003) include the standard optimal and robust control design techniques, both in time and frequency domain, while the modern approaches proposed by (Negm et al. 2003; Wang et al. 2003; Wang et al. 2009; Wong et al. 2011; Xiao-Feng et al. 2010) are based on the non-classical control designs viz. fuzzy logic, neural network, etc. A study of the literature reveals that with the design techniques available, transient behaviour of the system is a secondary feature in the Preview Control optimization problem. The use of adaptive control scheme with classical control techniques like PID, robust control (Anderson et al. 1997; Benaskeur et al. 2002; Eirea et al. 2008; Yu 1997; Zhao et al. 2008), etc has proved to be a successful combination to tackle transient behaviour in uncertain conditions. This paper proposes a unification of Adaptive Control and Preview Control that combines the advantages of both the schemes while avoiding their drawbacks and thus, presents design methodology for a novel control structure: Adaptive Preview Control (APC) for improved tracking quality of the system. The Adaptive Gain Update Law is formulated using Lyapunov's Theory and thus, the closed loop asymptotic stability of the system is guaranteed.

The paper is organised into five sections. The first section introduces the objective of the paper. The Adaptive Scheme for Preview Controller is explained and derived in the second section. The next section explains the design methodology for the problem. The fourth section presents the results of application of the methodology to the system models borrowed from the literature and the conclusion is drawn in the last section.

2. ADAPTIVE SCHEME FOR PREVIEW CONTROLLER

The general discrete-time system is described by

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) + Ed(k) \\ z(k) &= Cx(k) + Du(k) \end{aligned} \tag{1}$$

where $x(k) \in R^n$ and $u(k) \in R^m$ are the state vector and control input, respectively. The signal $z(k) \in R^p$ denotes the controlled output or the tracking error. Moreover, $d(k) \in R^l$ denotes the exogenous signal which can be considered as the reference signal or the disturbance.

The following assumptions are made for the system:

H1. (A, B) is stabilizable.

H2. $\begin{bmatrix} A-e^{j\theta}I & B \\ C & D \end{bmatrix}$ has full column rank for any $\theta \in [0, 2\pi)$.

H3. The values of $d(k), d(k+1), \ldots, d(k+h)$ are available for control, where h is a nonnegative constant that is called *preview length*.

The classical preview controller to be designed is of the form (Takaba 2003),

$$u(k) = K_x x(k) + \sum_{i=0}^{h} K_{di} d(k+i) \tag{2}$$

or, $K(z) = \begin{bmatrix} K_x & K_{d1} & \cdots & K_{dh} \end{bmatrix}$

The first and second terms on the right-hand-side of the controller equation (2) represent the state feedback and preview compensation, respectively.

The controller synthesis problem considered in this paper is to design a preview controller of the form shown in equation (2) such that the gains for the augmented previewed states can be modified online to adapt the changes in the reference trajectory. The structure of the Adaptive Preview Control scheme is as shown in figure 1. The preview action arises because of the delay line *Φ*. The input to the controller is *r*, which is the future value of the reference, and the Preview Controller *K* is chosen so as to ensure that *e* is small. The transient response of the system is further improved by adjusting the Preview Gains based on the present value of error *e* and reference *r* and thus, plant output follows *Φ(r)* as closely as possible.

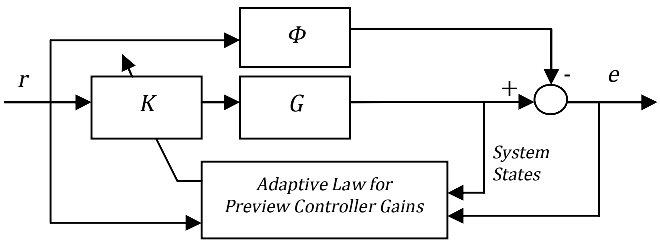

Fig. 1. Controller Structure with Adjustable Preview Gains.

3. DESIGN METHODOLOGY

The design procedure starts with the augmentation of the previewed information into system states.

The previewed information is available due to the delay line *Φ,* which can be represented as

$$x_d(k+1) = A_d x_d(k) + B_d d(k+h-1) \tag{3}$$

where $x_d(k)$ be the vector which represents the previewed information that is available for control, matrices A_d and B_d are defined as,

$$A_d = \begin{bmatrix} 0 & I & & 0 \\ & 0 & \ddots & \\ & & \ddots & I \\ 0 & & & 0 \end{bmatrix}, B_d = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ I \end{bmatrix} \tag{4}$$

Now, the augmented state vector can be defined as,

$$\xi(k) = \begin{bmatrix} x^T(k) & x_d^T(k) \end{bmatrix}^T \tag{5}$$

The augmented system (Takaba 2003), now, becomes,

$$\begin{aligned} \xi(k+1) &= F\xi(k) + Gu(k) + \bar{L}d(k) \\ z(k) &= H\xi(k) + Du(k) \end{aligned} \tag{6}$$

where

$$F = \begin{bmatrix} A & E & 0 \\ 0 & A_d & \end{bmatrix}, G = \begin{bmatrix} B \\ 0 \end{bmatrix}, \bar{L} = \begin{bmatrix} 0 \\ B_d \end{bmatrix}, H = \begin{bmatrix} C & 0 & 0 \end{bmatrix}$$

Thus, the preview controller is a state feedback law for the augmented system.

By applying the standard H∞ control theory to the augmented system, the solution to the Preview Control problem is obtained as follows:

Let a positive constant γ be given. There exists a stabilizing state feedback control with preview action satisfying the H∞ performance level

$$\sup \frac{\|z\|_2}{\|d\|_2} < \gamma \tag{7}$$

if and only if there exists a positive semi-definite stabilizing solution P to the following Algebraic Riccati Equation such that $W := \gamma^2 - \bar{L}^T P \bar{L} > 0$.

$$\begin{aligned} P &= F^T PF - \begin{bmatrix} G^T PF + D^T H \\ \bar{L}^T PF \end{bmatrix}^T V^{-1} \begin{bmatrix} G^T PF + D^T H \\ \bar{L}^T PF \end{bmatrix} + H^T H \\ V &= \begin{bmatrix} D^T D & 0 \\ 0 & -\gamma^2 I \end{bmatrix} + \begin{bmatrix} G^T \\ \bar{L}^T \end{bmatrix} P \begin{bmatrix} G & \bar{L} \end{bmatrix} \end{aligned} \tag{8}$$

In this case, one of the desired H∞ preview controller is given by

$$\begin{aligned} \begin{bmatrix} K_x & K_{d0} & \cdots & K_{dh} \end{bmatrix} &= -\left(D^T D + G^T \tilde{P} G\right)^{-1} \left(G^T \tilde{P} F + D^T H\right) \\ \tilde{P} &= P + P\bar{L}W^{-1}\bar{L}^T P \end{aligned} \tag{9}$$

The performance of the Preview Controller can be enhanced by allowing the controller to alter or modify its behaviour and thus, improve response of a plant to track a reference signal perfectly. The Adaptive Gain update Law is derived as below:

Theorem 3.1:

Consider a discrete-time system,

$$x(k+1) = Ax(k) + Bu(k) + Ed(k) \\ z(k) = Cx(k) \tag{10}$$

where $x(k) \in R^n$ and $u(k) \in R^m$ are the state vector and control input, respectively. The signal $y(k) \in R^p$ denotes the controlled output. The control signal is given by

$$u(k) = K_x x(k) + K_p r(k) \tag{11}$$

where $r(k) \in R^p$ is the reference signal, K_x is the static controller gain for system states and K_p is the static controller gain for previewed reference signals.

The control law is to be chosen such that the system as shown in (10) follows the model specified as below,

$$x_m(k+1) = A_m x_m(k) + B_m r(k) \\ y_m(k) = C_m x_m(k) \tag{12}$$

where $x_m(k) \in R^n$ are the reference model state vector and $y_m(k) \in R^p$ represents the reference model controlled output.

Let $P \in R^{n\times n}$ be the unique positive definite matrix satisfying,

$$A_m^T P A_m - P + L^T L = -Q \tag{13}$$

where norm bounded time varying non-linearity is assumed as $\psi\left(z(k),k\right) \in \psi_{br}$, such that,

$$\psi\left(z(k),k\right) = z^T(k) f^T(k) B^T P B f(k) z(k) \\ + A_m^T B z(k) \Gamma z^T(k) B^T P A_m \le L^T L \tag{14}$$

Consider the control law as shown in (11) with gain update presented by the following equation,

$$K_{k+1} = K_k - \Gamma z^T(k) B^T P A_m e(k) \tag{15}$$

where $\Gamma \in R^{n\times n}$ is a positive definite diagonal matrix.

Then, the solution of the closed – loop system defined by (10), (11), (13) and (14) is stable in Lyapunov sense and $e \to 0$ as $k \to \infty$.

Proof:

For the discrete-time system shown in (10), substituting the value of $u(k)$ from (11) gives,

$$x(k+1) = Ax(k) + B\left(K_x x(k) + K_p r(k)\right) \tag{16}$$

Further solving the above equation,

$$x(k+1) = (A + BK_x)x(k) + BK_p r(k) \tag{17}$$

As $K_x = K_x^* + \Delta\phi_x(k)$ and $K_p = K_p^* + \Delta\phi_p(k)$, then,

$$x(k+1) = \left(A + BK_x^* + B\Delta\phi_x(k)\right)x(k) + B\left(K_p^* + \Delta\phi_p(k)\right)r(k)$$

It is assumed that $A + BK_x^* = A_m$ and $BK_p^* = B_m$, then,

$$x(k+1) = A_m x(k) + B_m r(k) + B\Delta\phi_x(k)x(k) + B\Delta\phi_p(k)r(k)$$

or,

$$x(k+1) = A_m x(k) + B_m r(k) + B\phi(k)z(k) \tag{18}$$

where $\phi(k) = \begin{bmatrix}\Delta\phi_x(k) & \Delta\phi_p(k)\end{bmatrix}$ and $z(k) = \begin{bmatrix} x(k) \\ r(k)\end{bmatrix}$.

The error is defined as,

$$e(k) = x(k) - x_m(k) \tag{19}$$

Thus,

$$e(k+1) = x(k+1) - x_m(k+1)$$

Substituting the corresponding values from (12) and (18), we get,

$$e(k+1) = A_m x(k) + B_m r(k) + B\phi(k)z(k) - A_m x_m(k) - B_m r(k)$$

or,

$$e(k+1) = A_m e(k) + B\phi(k)z(k) \tag{20}$$

As, $\phi(k) = K(k) - K^*$, then,

$$\phi(k+1) = K(k+1) - K^*,$$

thus,

$$\phi(k+1) - \phi(k) = K(k+1) - K(k) \tag{21}$$

that is the gain update parameter. It is denoted by $\Delta\phi(k)$. The (21) can also, be written as,

$$\phi(k+1) = \phi(k) + \Delta\phi(k) \tag{22}$$

$\phi(k)$ is assumed to be a function of time and error value, defined as below,

$$\phi(k) = f(k)\cdot e(k) \tag{23}$$

Lets define a Lyapunov function,

$$V(k) = e^T(k)Pe(k) + \phi^T(k)\Gamma^{-1}\phi(k) \tag{24}$$

The Lyapunov difference is given by,

$$\Delta V = V(k+1) - V(k)$$

$$\Delta V = e^T(k+1)Pe(k+1) \\ + \phi^T(k+1)\Gamma^{-1}\phi(k+1) - e^T(k)Pe(k) - \phi^T(k)\Gamma^{-1}\phi(k) \tag{25}$$

Substituting the values from (20) and (22), we get,

$$\Delta V = e^T(k)\left(A_m^T P A_m - P\right)e(k) + 2e^T(k)A_m^T PB\phi(k)z(k)$$
$$+ z^T(k)\phi^T(k)B^T PB\phi(k)z(k)$$
$$+ 2\phi(k)\Gamma^{-1}\Delta\phi^T(k) + \Delta\phi^T(k)\Gamma^{-1}\Delta\phi(k)$$

Adding and subtracting $e^T(k)L^T Le(k)$, we get,

$$\Delta V = e^T(k)\left(A_m^T P A_m - P + L^T L\right)e(k) + 2e^T(k)A_m^T PB\phi(k)z(k)$$
$$+ z^T(k)\phi^T(k)B^T PB\phi(k)z(k) + 2\phi(k)\Gamma^{-1}\Delta\phi^T(k)$$
$$+ \Delta\phi^T(k)\Gamma^{-1}\Delta\phi(k) - e^T(k)L^T Le(k)$$

Using (13) and (23),

$$\Delta V = e^T(k)\left(-Q\right)e(k) + 2e^T(k)A_m^T PB\phi(k)z(k)$$
$$+ z^T(k)e^T(k)f^T(k)B^T PBf(k)e(k)z(k) + 2\phi(k)\Gamma^{-1}\Delta\phi^T(k)$$
$$+ \Delta\phi^T(k)\Gamma^{-1}\Delta\phi(k) - e^T(k)L^T Le(k)$$

Using the gain update law as, $\Delta\phi(k) = -\Gamma z^T(k)B^T PA_m e(k)$, in the above equation,

$$\Delta V = e^T(k)\left(-Q\right)e(k) + 2e^T(k)A_m^T PB\phi(k)z(k)$$
$$+ z^T(k)e^T(k)f^T(k)B^T PBf(k)e(k)z(k) + 2\phi(k)\Gamma^{-1}\left(-\Gamma z^T(k)B^T PA_m e(k)\right)^T$$
$$+ \left(-\Gamma z^T(k)B^T PA_m e(k)\right)^T \Gamma^{-1}\left(-\Gamma z^T(k)B^T PA_m e(k)\right)$$
$$- e^T(k)L^T Le(k)$$

Simplifying the above equation,

$$\Delta V = -e^T(k)Qe(k) + z^T(k)e^T(k)f^T(k)B^T PBf(k)e(k)z(k)$$
$$+ e^T(k)A_m^T Bz(k)\Gamma z^T(k)B^T PA_m e(k) - e^T(k)L^T Le(k)$$

or,

$$\Delta V = -e^T(k)Qe(k)$$
$$+ e^T(k)\left(z^T(k)f^T(k)B^T PBf(k)z(k) + A_m^T Bz(k)\Gamma z^T(k)B^T PA_m - L^T L\right)e(k)$$

Using (14),

$$\Delta V = -e^T(k)Qe(k) + e^T(k)\left(\psi\left(z(k),k\right) - L^T L\right)e(k)$$

Since Q is positive definite and $\psi\left(z(k),k\right) - L^T L \le 0$ for all $\psi\left(z(k),k\right) \in \psi_{br}$. It follows that the Lyapunov difference ΔV is negative definite. Hence, the solution is asymptotically stable.

The above derived adaptive parameter update law, (8), with the Preview Control Scheme has been applied to evaluate the performance of typical systems.

4. APPLICATION RESULTS

The implementation of the procedure was carried out on MATLAB platform for two benchmark systems. The plant models are initially expressed in the form,

$$x_p(k+1) = A_p x_p(k) + B_p u_p(k)$$
$$y_p(k) = C_p x_p(k) + D_p u_p(k) \qquad (26)$$

where $x_p(k)$ is the state vector, $u_p(k)$ is the control vector and $y_p(k)$ is the output vector of the plant. The system in this format is converted to the standard form expressed by (1) to include the reference information. The results for the systems are presented as follows,

4.1 Servomechanism

The servomechanism consists of a motor connected with load whose angular position is to be controlled. The state vector x_p in this case is defined as $x_p{}^T = \begin{bmatrix}\theta_M & \theta_L & w_M & w_L\end{bmatrix}^T$, where θ_M is the motor shaft angle, θ_L is the load angle, w_M is the motor shaft's angular velocity and w_L is the load angular velocity. The control signal u_p is physically the voltage applied to the motor and the output signal y_p is the load angle θ_L.

The state-variable model of the 4[th]-order Servomechanism (Takaba (2003)) is expressed in the form presented in the (26) with the state-space matrices as:

$$A = \begin{bmatrix} 0.9752 & 0.0248 & 0.1983 & 0.0017 \\ 0.0248 & 0.9752 & 0.0017 & 0.1983 \\ -0.2459 & 0.2459 & 0.9752 & 0.0248 \\ 0.2459 & -0.2459 & 0.0248 & 0.9752 \end{bmatrix};$$

$$B = \begin{bmatrix} -0.0199 \\ -0.0001 \\ -0.1983 \\ -0.0017 \end{bmatrix}; C = \begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}; D = \begin{bmatrix} 0 \end{bmatrix}$$

The values of the parameters chosen for classical design are:

$$Q = 20, R = 1, \gamma = 27.36$$

A comparison of the time-response of system designed using adaptive control theory only without any preview, with a preview length of *h=7* designed using classical H∞ control theory and with preview length of *h=7* designed using Lyapunov based Adaptive Preview Control methodology, assuming that there is no disturbance in the system, is shown in figure 2.

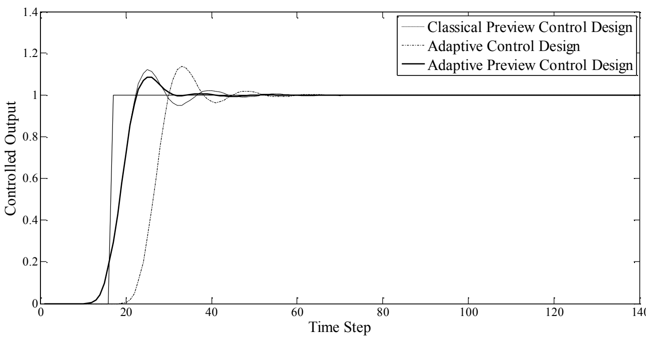

Fig. 2. Transient Step Response of Servomechanism.

The transient characteristics, obtained in response to the step signal, of Servomechanism are summed up in table 1.

Table 1. Transient Response Characteristics of Servomechanism.

System Characteristics	Adaptive Control Design	Classical Preview Control Design	Adaptive Preview Control Design
Peak Overshoot (%)	13.8	12.2	8.6
Peak Time (s)	33	25	25
Settling Time (s)	38	34	28.5
IAE	10.6221	3.4556	3.0034

4.2 2DOF Helicopter

The model of 2DOF helicopter (Quanser 2DOF Helicopter User Manual, (Cazzolato 2006), considered in this section, is a muti-input multi-output non linear system. The non linear dynamic equations are not available in the product catalogue. However a derivation has been presented in appendix A. The proposed procedure is applied to linearized model of 2DOF helicopter, obtained for the assumptions considered in appendix A. The state vector for this model is defined as $x_p{}^T = \begin{bmatrix}\theta & \psi & \dot\theta & \dot\psi\end{bmatrix}^T$, where θ is the pitch angle, ψ is the yaw angle, $\dot\theta$ is the pitch angular velocity and $\dot\psi$ is the yaw angular velocity. The control vector $u_p{}^T = \begin{bmatrix}\delta v_p & \delta v_y\end{bmatrix}^T$ consists of the force on the front and back motors, physically the voltage applied to the pitch and the yaw motor, respectively, to control their speeds. The output vector $y_p{}^T = \begin{bmatrix}\theta & \psi\end{bmatrix}^T$ consists of the pitch and the yaw angles, respectively. The model is discretized with sample time $t_s = 0.5$ seconds. The state space matrices of the considered model, for the form as in (26), are presented in appendix A.

The model is augmented to include the error signals and the previewed information. The proposed algorithm is applied to the obtained model and simulations are carried out. The results obtained are presented as below:

A comparison of the time-response of system designed with adaptive control theory only without preview, with a preview length of *h=10* designed using classical H∞ control theory and with preview length of *h=10* designed using Lyapunov based Adaptive Preview Control methodology, assuming that there is no disturbance in the system, is shown in figure 3.

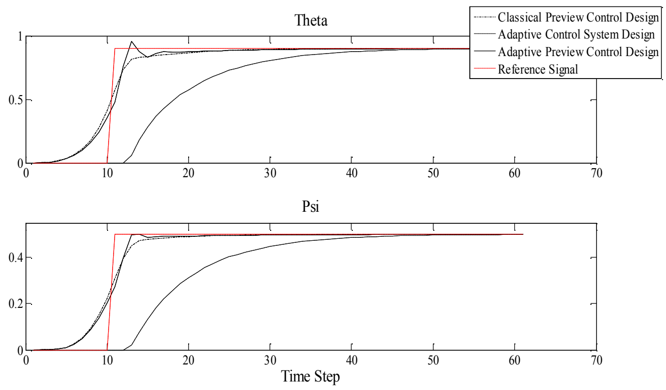

Fig. 3(a). Transient Response of 2DOF Helicopter (θ & ψ).

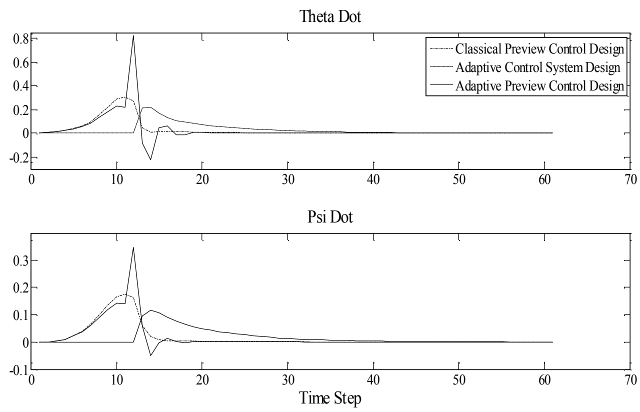

Fig. 3(b). Transient Response of 2DOF Helicopter ($\dot\theta$ & $\dot\psi$).

The transient characteristics in response to the constant command signal $\begin{bmatrix}\theta & \psi\end{bmatrix} = \begin{bmatrix}0.9 & 0.5\end{bmatrix}$ of 2DOF Helicopter model are summed up in table 2 and 3.

Table 2. Transient Response Characteristics of 2DOF Helicopter (θ).

System Characteristics	Adaptive Control Design (θ)	Classical Preview Control Design (θ)	Adaptive Preview Control Design (θ)
Peak Overshoot (%)	-	-	5.87
Peak Time (s)	-	-	13
Settling Time (s)	38	19	16
IAE	8.4991	2.2628	2.1222

Table 3. Transient Response Characteristics of 2DOF Helicopter (ψ).

System Characteristics	Adaptive Control Design (ψ)	Classical Preview Control Design (ψ)	Adaptive Preview Control Design (ψ)
Peak Overshoot (%)	-	-	-
Peak Time (s)	-	-	-
Settling Time (s)	38	16	13
IAE	4.8471	1.0922	0.999

The results establish the tracking capability of the Adaptive Preview Controller. The transient response of the system improves as judged by the major transient characteristics. The Adaptive Preview Control Gain update Law designed using Lyapunov function improves the systems' response, substantially, as well as, sustains the asymptotic stability of the closed-loop system.

5. CONCLUSION

This paper presents a design of Adaptive Preview Control based on Lyapunov formulation for discrete-time systems. As the formulation is based on Lyapunov function, it guarantees the asymptotic stability of the closed-loop system. The system's ability to track is improved by the use of a priori knowledge of the reference trajectory. The ability to track can further be enhanced by the use of Adaptive law to modify the Preview Gains, based on the present value of error and states. The performance of the benchmark systems tested with the proposed design technique validates the performance improvement over the existing techniques. The application of evolutionary computing in the APC will be reported in further communications.

REFERENCES

Akbari, A., Koch, G., Pellegrini, E., Spirk, S., and Lohmann, B., (2010). Multi-objective Preview Control of Active Vehicle Suspensions: Experimental Results. *Proceedings of the 2nd International Conference on Advanced Computer Control (ICACC), Shenyang*, 3, 497-502.

Anderson, E.H., and How, J.P., (1997). Adaptive Feed-forward Control for Actively Isolated Spacecraft Platforms. *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference and Exhibit, Kissimmee, FL, AIAA-1997-1200*, 1-11.

Benaskeur, A.R. and Desbiens, A., (2002). Backstepping-based Adaptive PID Control. *IEE Proceedings – Control Theory and Applications*, 149(1), 54-59.

Cazzolato, B., (2006). *Automatic Control II – 2DOF Helicopter Tutorial*.

Egami, T., and Tsuchiya, T., (1995). Disturbance Supression Control with Preview Action of Linear DC Brushless Motor. *IEEE Transactions on Industrial Electronics*, 42(5), 494-500.

Eirea, G., and Sanders, S.R., (2008). Adaptive Output Current Feedforward Control in VR Applications. *IEEE Transactions on Power Electronics*, 24(4), 1880-1887.

Farooq, A., and Limbeer, D.J.N., (2005). Path Following of Optimal Trajectories Using Preview Control. *Proceedings of the 44th IEEE Conference on Decision and Control and the European Control Conference 2005, Spain*, 2787-2792.

Hazawa, K., Shin, J., Fujiwara, D., Igarashi, K., Fernando, D., and Nonami, K., (2004). Autonomous Flight Control of Hobby-Class Small Unmanned Helicopter. *Proceedings of the 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2004), Japan*, 1, 754-760.

Jensen, R. and Neilsen, A.K.N., (2005). *Robust Control of an Autonomous Helicopter*. Master of Science Thesis, Aalborg University, Denmark.

Kadakkal, V., and Cook, G. (2008). Use of a Preview Control Scheme with Knowledge of Future Trajectory Information for a Lane Tracking Controller on a Wheeled Mobile Robot. *Proceedings of 34th Annual Conference of IEEE on Industrial Electronics, Florida* 1692-1697.

Kanzaki, S., Okada, K., and Inaba, M., (2005). Bracing Behavior in Humanoid through Preview Control of Impact Disturbance. *Proceedings of 2005 5th IEEE-RAS International Conference on Humanoid Robots, Tsukuba*, 301-305.

Kojima, A. and Ishijima, S., (1997). H∞ Control with Preview Compensation. *Proceedings of the 1997 American Control Conference, USA*, 3, 1692-1697.

Kojima, A., and Ishijima, S., (1998). H∞ Preview Disturbance Attenuation. *Proceedings of the 37th IEEE Conference on Decision and Control, USA*, 3, 3201-3203.

Kojima, A., and Ishijima, S., (1999). H∞ Preview Tracking in Output Feedback Setting. *Proceedings of the 38th IEEE Conference on Decision and Control, USA*, 3, 3162-3164.

Kojima, A., and Ishiijima, S., (2003). H∞ Performance of Preview Control Systems. *Automatica*, 39(4), 693-701.

Kojima, A., and Ishijima, S., (2006). Formulas on Preview and Delayed H∞ Control. *IEEE Transactions on Automatic Control*, 51(12), 1920-1937.

Kristalny, M. and Mirkin, L., (2010). Preview in H2 Optimal Control: Experimental Case Studies. *Proceedings of the 49th IEEE Conference on Decision and Control, USA*, 6004 – 6009.

Liao, Fu-Cheng., Cui, Ya-Hong., and Shen, Zheng-Wei., (2009). Optimal Preview Control for Linear Time-Variant Discrete Systems. *Proceedings of the 8th International Conference on Machine Learning and Cybernetics, Baoding*, 4, 1954-1960.

Mianzo, L., and Peng, H., (1998). A Unified Framework for LQ and H∞ Preview Control Algorithms. *Proceedings of* *the 37th IEEE Conference on Decision and Control, Florida*, 3, 2816-2821.

Mianzo, L., and Peng, H., (2007). Output Feedback H∞ Preview Control of an Electromechanical Valve Actuator. *IEEE Transactions on Control Systems Technology*, 15(3), 428-437.

Mil', M.L., Nekrasov, A.V., Braverman, A.S., Grodko, L.N., and Leykand, M.A., (1967). *Helicopters Calculation and Design*. Mashinostroyeniye Publishing House, Moscow, 1966; NASA Technical Translation, Washington.

Moran, A., Mikami, Y., and Hayase, M., (1996). Analysis and Design of H∞ Preview Tracking Control Systems. *Proceedings of 1996 4th International Workshop on Advanced Motion Control*, 2, 482-487.

Negm, M.M.M., and Kheireldin, A.F., (1991). Properties of adaptive, optimal and preview controllers based on MVC and LQS optimal controller application to robotic manipulator. *Proceedings of the International Conference on Control, Edinburgh*, 1, 323-328.

Negm, M.M., Mantawy, A.H. and Shwehdi, M.H., (2003). A Global ANN Algorithm for Induction Motor Based on Optimal Preview Control Theory. *Proceedings of the 2003 IEEE Bologna Power Tech Conference, Itlay*, 2, 1-7.

Negm, M.M.M., Bakhashwain, M., and Shwehdi, M.H., (2006). Speed Control of a Three-Phase Induction Motor Based on Robust Optimal Preview Control Theory. *IEEE Transactions on Energy Conversion*, 21(1), 77-84.

Quanser 2DOF Helicopter User Manual accessed from http://www.quanser.com/.

Silvestre, C., Cunha, R., Paulino, N., and Pascoal, A., (2009). A Bottom-Following Preview Controller Autonomous Underwater Vehicles. *IEEE Transactions on Control Systems Technology*, 17(2), 257-266.

Sumer, E.D., Lu, J., Filev, D.P., Hoagg, J.B., and Bernstein, D.S., (2010). Adaptive Road-Following Preview Control Using Radius of Curvature Data. *Proceedings of the 2010 American Control Conference, USA*, 4806 – 4811.

Tadmor, G., and Mirkin, L., (2003). H∞ Preview Control and Fixed-Lag Smoothing I: Matrix ARE Solutions in Continuous-Time Systems. *Proceedings of the 42nd IEEE Conference on Decision and Control, USA*, 6515-6520.

Tadmor, G., and Mirkin, L., (2003). H∞ Preview Control and Fixed-Lag Smoothing II: Fixed Size ARE Solutions in Discrete-Time Systems. *Proceedings of the 42nd IEEE Conference on Decision and Control, USA*, 6521-6526.

Takaba, K., (1998). Robust Preview Tracking Control for Polytopic Uncertain Systems. *Proceedings of the 37th IEEE Conference on Decision and Control, Florida*, 2 1765 - 1770.

Takaba, K., (2000). Robust Servomechanism with Preview Action for Polytopic Uncertain Systems. *International Journal of Robust and Nonlinear Control*, 10(2), 101–111.

Takaba, K., (2003). A Tutorial on Preview Control Systems. *Proceedings of the SICE Annual Conference, Fukui*, 2, 1388 – 1393.

Tian, M.-Q., and Xiong, S.-B., (2002). Previewing control system of automatic height adjustment for drum-type coal excavator based on memory cutting with identification of object model by genetic algorithm. *Proceedings of 2002 International Conference on Machine Learning and Cybernetics, China*, 2, 633 – 636.

Tomizuka, M., (1975). Optimal Continuous Finite Preview Problem. *IEEE Transactions on Automatic Control*, 20(3), 362-365.

Tsuchiya, T., Shinada, K., Abe, S. and Egami, T., (1988). Robot Trajectory Control By Preview Control and Adaptive Control. *Proceedings of the IEEE Workshop on Intelligent Robots*, 125-130.

Velagic, J., Osmic, N., Zunic, E., Uzunovic, T., and Badnjevic, A., (2010). Design of 3D Simulator for 2DOF Helicopter Model Control. *Proceedings of ELMAR*, 305-308.

Wang, D., and Aida, K., (2003). Research on Fuzzy I-PD Preview Control for Nonlinear System. *JSME International Journal, Series C*, 46(3), 1042-1050.

Wang, H., Zhang, H., Xie, L., and Liu, S., (2009). Discrete Time H∞ Preview Control. *Proceedings of the 7th Asian Control Conference, China*, 57-62.

Wong, P.-K., Xie, Z., Wong, H.-C. and Huang, X., (2011). Design of a Fuzzy Preview Active Suspension System for Automobiles. *Proceedings of the 2011 International Conference on System Science and Engineering, China*, 525 – 529.

Xiao-Feng, L., Mu-Qin, T., Lvyong-Wei and Shu-Hua, W., (2010). Study on Preview Control Theory for Trajectory Tracking Control. *Proceedings of the 2010 International Conference on Computational Aspects of Social Networks (CASoN), Taiyuan*, 445 – 447.

Yan, L., and Shaojun, L., (2009). Preview Control of an Active Vehicle Suspension System Based on a Four-Degree-of-Freedom Half-Car Model. *Proceedings of the International Conference on Measuring Technology and Mechatronics Automation (ICMTMA '09)*, 1, 563-567.

Yim, S., (2011). Design of a Preview Controller for Vehicle Rollover Prevention. *IEEE Transactions on Vehicular Technology*, 60(9), 4217-4226.

Yokoyama, K., and Kojima, A., (2009). H2 performance on Multiple Preview Compensation. *Proceedings of the ICROS-SICE International Joint Conference 2009, Japan*, 93-97.

Yu, G.R., (2007). Robust-Optimal Control of a Nonlinear Two Degree-of-Freedom Helicopter. *Proceedings of IEEE/ACIS International Conference on Computer and Information Science*, 744-749.

Yu, H., (1997). Variable Structure Adaptive Control of Robot Manipulators. *IEE Proceedings – Control Theory and Applications*, 144(2), 167-176.

Zhao, D., Li, S., and Gao, F., (2008). Fully Adaptive Feedforward Synchronized Tracking Control for Stewart Platform Systems. *International Journal of Control, Automation and Systems*, 6(5), 689-701.

Appendix A. 2DOF HELICOPTER MODEL

The equations of motions of two degrees of freedom Helicopter model are given by,

$$J_p\ddot{\theta} + J_y \sin\theta\cos\theta\dot{\psi}^2 + mg\left(h\sin\theta + R_c\cos\theta\right) + c_p\dot{\theta} = lk_{pp}v_p + k_{py}v_y$$

$$\left(J_p\cos(\theta)^2 + J_{shaft}\right)\ddot{\psi} - 2J_p\cos\theta\sin\theta\dot{\theta}\dot{\psi} + c_y\dot{\psi} = lk_{yy}v_y\cos\theta + k_{py}v_y\cos\theta$$

These equations are linearized about the level flight, with the assumption of the states as $x_1 = \theta, x_2 = \psi, x_3 = \dot{\theta}$ and $x_4 = \dot{\psi}$, the state space representation of the system is,

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ \frac{-mgh}{J_p} & 0 & \frac{-c_p}{J_p} & 0\\ 0 & 0 & 0 & \frac{-c_y}{J_y}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix} + \begin{bmatrix} 0 & 0\\ 0 & 0\\ \frac{lk_{pp}}{J_p} & \frac{k_{py}}{J_p}\\ \frac{lk_{yp}}{J_y} & \frac{k_{yy}}{J_y}\end{bmatrix}\begin{bmatrix}\delta v_p\\ \delta v_y\end{bmatrix}$$

$$\begin{bmatrix}y_1\\ y_2\end{bmatrix} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\end{bmatrix}$$

where $J_y = J_p + J_{shaft}$, $\delta v_p = v_p - v_{pe}$, $\delta v_y = v_y - v_{ye}$, v_{pe} is the pitch equilibrium voltage and v_{ye} is the yaw equilibrium voltage.

The model parameters chosen are as below,

Table 4. 2DOF Helicopter Model Parameters.

Parameter	Value
k_{pp}	0.185*0.20962 N/V
k_{yy}	0.185*0.050271 N/V
k_{yp}	0.0083316 N-m/V
k_{py}	0.0041362 N-m/V
J_p	0.0500 kg-m^2
J_y	0.0500+0.0039 kg-m^2
c_p	0.0100000 kg-m^2/s
c_y	0.0071428 kg-m^2/s
m	1.326 kg
l	0.0168 m
h	0.0139 m
R_c	0.0094 m
g	9.81 m/s^2