Design of High Accuracy Tracking Systems with $H_{\infty}$ Preview Control

Antonio Moran Cardenas, Javier G. Rázuri, Isis Bonet, Rahim Rahmani, and David Sundgren

Abstract—Positioning and tracking control systems are an important component of autonomous robot applications. This paper presents the design method of tracking control systems based on $H_{\infty}$ preview control where the present and future desired positions of the robot are used to determine the control actions to be applied so that the robot describes the desired trajectory as close as possible. The performance improvements achieved with $H_{\infty}$ preview control have been examined in the frequency and time domains for different types of reference signals when applied to a one-dimensional positioning system. It was found that preview control improves the tracking performance by improving the phase response of the tracking system.

Index Terms—Robotics, planning and scheduling, predictive control, $H_{\infty}$ control, tracking control, control $H_2$, frequency-domain analysis, time-domain analysis.

I. INTRODUCTION

PRECISE positioning/tracking control is being studied in many manufacturing fields in order to improve the accuracy and performance of manufacturing process and manipulator driving systems which every time demand more precise, robust and efficient control systems [1]. Certain behavior is desired in positioning/tracking control systems: fast response and convergence, zero tracking error and robustness against changes in the system itself and/or its environment.

The classical way to solve the tracking control problem for linear time-invariant systems has been to design a one-degree-of-freedom, or better, a two-degrees-of-freedom controller which will achieve the desired performance as close as possible. The inherent shortcoming of the classical approach is the overdesign that is entitled in requiring a close as possible. The inherent shortcoming of the classical controller which will achieve the desired performance as one-degree-of-freedom, or better, a two-degrees-of-freedom for linear time-invariant systems has been to design a controller against changes in the system itself and/or its environment.

In Section IV, we described the formulation process related to the generalized plant. Experimental results and discussion are presented in Section V, while Section VI presents some conclusions of the research.
II. EXPERIMENTAL SYSTEM

A. Experimental System

Figure 1 shows the structure of the experimental positioning/tracking system. A DC motor rotates a ballscrew to longitudinally move a positioning stage which is composed of a main stage and a sub-stage connected through two flexible plate springs. The control objective is to place the sub-stage in an arbitrary desired position or to follow any desired trajectory. To do that, a laser position sensor measures the position of the sub-stage and sends the measured signal to a computer which calculates a control voltage according to the algorithm of the $H_{\infty}$ controller. Using a power amplifier, the control signal is applied to the DC motor to control the rotational motion of the ballscrew in order to achieve the desired motion of the sub-stage. The DC motor and main stage are affected by friction torque and friction forces, respectively. The sub-stage moves on a rough surface whose degree of roughness (friction) may be varied to analyze the robustness of the system against external friction forces.

B. Vibrational Model

Figure 2 shows the equivalent vibrational model of the positioning/tracking mechanism. The flexible plates are modeled as a linear spring with stiffness $K_{sp}$. The rotational damping of the DC motor is represented by $K_{cr}$ and the friction torque by $T_f$. External forces acting on the sub-stage are represented by linear damping $K_{cl}$ and friction force $F_f$.

III. STATE EQUATION MODEL

A. Nominal Model

Neglecting the inductance of the DC motor, its dynamics can be described by the following equation:

$$\frac{R_a}{K_t} T = K_{pa} u - K_c \dot{\theta},$$

where $T$ and $u$ are the torque and voltage of the DC motor and $\dot{\theta}$ is the angular velocity of the ballscrew. The rotational motion equation of the driving mechanism (motor shaft and ballscrew) is given by

$$T - T_f - T_{qr} = J \ddot{\theta} + K_{cr} \dot{\theta},$$

where $T_f$ is the Coulomb friction torque and $T_{qr}$ is an equivalent torque representing the rotational effect of the inertia of the main stage and is equal to

$$T_{qr} = K_{sp} K_{bs} (x_m - x_s),$$

where $x_m$ and $x_s$ represent the position of the main stage and sub-stage, respectively. The linear motion equation of the sub-stage is given by

$$(x_m - x_s) K_{sp} - F_f = M \ddot{x}_s + K_{cl} \dot{x}_s,$$

where $F_f$ is the friction force affecting the sub-stage and $M$ is the mass of the sub-stage. Defining the state vector:

$$\bar{x} = [\dot{\theta}, \theta, \dot{x}_s, x_s]^T,$$

and combining Equations 1 to 4, the following state-space equation of the nominal system $P$ can be formulated:

$$\dot{\bar{x}} = A \bar{x} + B_1 \bar{w} + B_2 u,$$

where $\bar{w} = [T_f, F_f]^T$. The parameters specifications are shown in Table I.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>Power amplifier gain</td>
<td>$K_{pa}$</td>
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</tr>
<tr>
<td>DC motor resistance</td>
<td>$R_a$</td>
<td>1.1 ohm</td>
</tr>
<tr>
<td>DC motor torque constant</td>
<td>$K_t$</td>
<td>0.0573 N.m/A</td>
</tr>
<tr>
<td>Back electromotive force constant</td>
<td>$K_e$</td>
<td>$5.665 \times 10^{-2}$ v.s</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>$J$</td>
<td>$4.326 \times 10^{-5}$ kg.m^2</td>
</tr>
<tr>
<td>Rotational damping factor</td>
<td>$K_{cr}$</td>
<td>4.550 x $10^{-3}$ N.m.s</td>
</tr>
<tr>
<td>Ballscrew transducing coefficient</td>
<td>$K_{bs}$</td>
<td>1.509 x $10^{-3}$ m/rad</td>
</tr>
<tr>
<td>Spring stiffness</td>
<td>$K_{sp}$</td>
<td>264 N/m</td>
</tr>
<tr>
<td>Linear damping factor</td>
<td>$K_{cl}$</td>
<td>0.747 N.s/m</td>
</tr>
<tr>
<td>Mass of sub-stage</td>
<td>$M$</td>
<td>0.244 kg</td>
</tr>
</tbody>
</table>
B. Generalized Plant with Integral Action

In order to design a controller with integral action to eliminate steady-state tracking errors, the generalized plant used for designing the controller is structured considering integral action. To do that, Equation 6 representing the nominal plant, is integrated with the equation of the tracking error \( e \) given by the expression:

\[
e = r - x_s,
\]

where \( r \) is the reference signal to be tracked. Defining the state vector

\[
x = \left[ \theta, \dot{\theta}, x_s, x_s \int (r - x_s) dt \right]^T,
\]

the state-space equation of the generalized plant with integral action is:

\[
\dot{x} = Ax + B_1p\dot{w} + B_2u + B_r r,
\]

where it can be noted that the reference signal \( r \) is not included in the disturbance vector \( \dot{w} \). Matrices \( A, B_1p, B_2 \) and \( B_r \) are obtained by combining Equations 6 and 7.

IV. \( H_\infty \) Preview Control Law

As it is well known, the first step for designing an \( H_\infty \) controller is the formulation of the generalized plant. By defining the controlled output vector \( z \) as

\[
z = \left[ \rho_1 x_s, \rho_2 x_s, \rho_3 \int (r - x_s) dt, u \right]^T,
\]

and the measured output vector \( y \) as:

\[
y = \left[ x_s + \eta_1 \int (r - x_s) dt + \eta_2 \right],
\]

the equations describing the generalized plant \( P \) are:

\[
\begin{align*}
\dot{x} &= Ax + B_1w + B_2u + B_r r \\
z &= C_1x + D_{12}u \\
y &= C_2x + D_{21}u
\end{align*}
\]

where the disturbance vector \( w = [T_f, F_r, \eta_1, \eta_2]^T \) and \( B_1 = [B_1^T, 0]^T \). Factors \( \rho_1, \rho_2 \) and \( \rho_3 \) in Equation 10 are weighting coefficients selected to tailor the performance and robustness specifications. \( \eta_1 \) and \( \eta_2 \) in Equation 11 represent measurement noise which are assumed to be independent of the plant disturbances \( w \). Given this assumption, matrices \( B_1 \) and \( D_{21} \) turn to be orthogonal. Also, given the components of the controlled output \( z \), matrices \( C_1 \) and \( D_{12} \) are orthogonal. The structure of the generalized plant is shown in Figure 3 (to gain clarity, the controlled output \( z \) is not shown).

According to \( H_\infty \) control theory, given the generalized plant \( P \), a controller is designed so that the \( H_\infty \) norm of the transfer function \( T_{zw} \) from disturbances \( w \) to controlled output \( z \) is less than a given scalar \( \gamma \):

\[
\|T_{zw}\| < \gamma.
\]

Optimal \( H_\infty \) controllers are designed for the minimum value of \( \gamma \) and \( H_2 \) controllers are designed for \( \gamma = \infty \). By analogy with Game Theory, the \( H_\infty \) control problem can be expressed as the minimization of the following cost function:

\[
J = \int [z^T z - \gamma^2 w^T w] dt,
\]

which can be expanded as:

\[
J = \int_0^\infty [x^T C_1^T C_1 x + [w^T u^T] \begin{bmatrix} -\gamma^2 & 0 \\ 0 & R \end{bmatrix} [w^T u^T]] dt,
\]

where \( R = D_{12}^T D_{12} \). The conventional approach to design \( H_\infty \) tracking systems has been to formulate a generalized plant which includes the reference signal as external disturbance and design a one or two-degrees-of-freedom controller which will achieve the desired specifications. The inherent shortcoming of this approach is the overdesign that is entitled when designing a controller independently of the reference signal to be tracked which is known a priori.

\[
\dot{w} = [T_f, F_r, \eta_1, \eta_2, r]^T.
\]

In other words, a controller is designed for the worst reference signal \( r_{\text{worst}} \) which, is, for the most of cases, different to the desired reference signal \( r \). To overcome the shortcoming of the classical \( H_\infty \) approach, this paper proposes \( H_\infty \) preview control where the known reference signal is used, as it is, for designing the controller. The design of the \( H_\infty \) preview controller has been divided in two parts: first, \( H_\infty \) preview control laws have been derived for the case of state feedback, and afterwards an observer was designed considering the conventional approach to design \( H_\infty \) output feedback controllers. The structure of the \( H_\infty \) preview controller is shown in Figure 3 where it can be noted the feedback part \( K_f \) and preview part \( K_p \) of the controller. \( H_\infty \) control laws have been derived for two cases: (1) the reference signal is known for the total working time and (2) the reference signal is previewed for a fixed interval of time shorter than the total working time.
A. Reference signal known for the total working time

When the reference signal is known for the total working time \([t, t + T]\), the \(H_\infty\) preview controller is designed considering the generalized plant of Equations 12 and 13 and the following cost function:

\[
J = \int_t^{t+T} [z^T z - \gamma^2 w^T w] \, dt
\]  \hspace{1cm} (18)

Using the Hamiltonian approach of Optimal Control Theory [19], the preview control law which minimizes the cost function of Equation 18 subject to the constraint of Equation 12 is given by:

\[
u(t) = -R^{-1}B_2^T [P(t)x(t) + q(t)],
\] \hspace{1cm} (19)

where \(P(t)\) is the solution of the following differential Riccati equation:

\[
-P(\tau) = P(\tau)A - P(\tau)(B_2R^{-1}B_2^T - \gamma^{-2}B_1B_1^T)P(\tau) + \gamma^{-2}B_1B_1^TP(\tau) + A^T P(t) + C_1^T C_1,
\] \hspace{1cm} (20)

with \(t \leq \tau \leq t + T\) and \(P(\tau)\) satisfying the terminal constraint:

\[
P(t + T) = 0;
\]

\(q(t)\) in Equation 12 is the solution of the following differential equation:

\[
-q(t) = (A^T - P(\tau)(B_2R^{-1}B_2^T - \gamma^{-2}B_1B_1^T))q(\tau) + \gamma^{-2} B_1 r(\tau) + PB_1 r(\tau),
\] \hspace{1cm} (21)

satisfying the terminal constraint:

\[
q(t + T) = 0.
\]

Since to compute \(q(t)\) and \(P(t)\), Equations 20 and 21 should be integrated backwards in time, the computational amount could turn cumbersome and impractical so that an approximated simplification easy to compute is necessary. Assuming the working time \(T\) is long enough so that \(P(t) = 0\) and \(P = \text{const}\), \(q(t)\) can be calculated from the following equation:

\[
q(t) = \exp\left[-(A_0^T + M)t\right] x \int_t^{t+T} \exp\left[(A_0^T + M)\tau\right] PB_1 r(\tau) \, d\tau,
\] \hspace{1cm} (22)

where

\[
A_0 = A - B_2R^{-1}B_2^T P
\] \hspace{1cm} (23)

and

\[
M = \gamma^{-2}B_1B_1^T P.
\] \hspace{1cm} (24)

\(A_0\) in Equation 23 represents the state matrix of the closed-loop system for the case of only feedback control. It is important to note that the control law of Equation 19 has the structure of two-degrees-of-freedom controllers with feedback and feedforward (preview) parts so that preview control improves the tracking performance of the system without affecting its feedback characteristics (stability, disturbance attenuation, etc.).

B. Reference signal previewed for a fixed interval of time

In this case it is assumed the reference signal is known for a fixed interval of time \(T\) which is much shorter than the total working time assumed to be long enough. In this case, the cost function to be optimized is

\[
J = \int_t^\infty [z^T z - \gamma^2 w^T w] \, d\tau,
\] \hspace{1cm} (25)

which can be decomposed in two parts:

\[
J = \int_t^{t+T} [z^T z - \gamma^2 w^T w] \, d\tau + \int_{t+T}^\infty [z^T z - \gamma^2 w^T w] \, d\tau,
\] \hspace{1cm} (26)

where

\[
J_1 = \int_t^{t+T} [z^T z - \gamma^2 w^T w] \, d\tau
\]

and

\[
J_2 = \int_{t+T}^\infty [z^T z - \gamma^2 w^T w] \, d\tau
\]

Since the reference signal \(r\) is only known for the interval \([t, t + T]\), it is not included as a component of the disturbance vector \(w\) for this interval (cost function \(J_1\)), but it is included in \(w = \hat{w}\) for the interval \([t + T, \infty]\). Since in this interval \(r\) is not known it should be replaced by \(r_{\text{worst}}\) as in standard \(H_\infty\) tracking control. From Linear Optimal Control Theory it is well known that the minimum value of the cost function \(J_2\) is

\[
J_2 = x^T(t + T) \hat{P} x(t + T) + \int_{t+T}^\infty [z^T z - \gamma^2 w^T w] \, d\tau
\] \hspace{1cm} (27)

where \(\hat{P}\) is the solution of the following algebraic Riccati equation:

\[
\hat{P}A - \hat{P}(B_2R^{-1}B_2^T - \gamma^{-2}(B_1B_1^T + B_3B_3^T))\hat{P} + \gamma^{-2}B_1B_1^T\hat{P} + C_1^T C_1 = 0
\] \hspace{1cm} (28)

From Equations 26 and 27, the cost function \(J\) can be expressed as:

\[
J = x(t + T) \hat{P} x(t + T) + \int_t^{t+T} [z^T z - \gamma^2 w^T w] \, dt
\] \hspace{1cm} (29)

Since the cost functions of Equations 29 and 18 are similar with the only difference being the term \(x(t + T) \hat{P} x(t + T)\) in Equation 29, the control law which minimizes the cost function \(J\) of Equation 29 subject to the constraint of Equation 12, is also given by Equation 19 with \(P(t)\) calculated from Equation 20 and \(q(t)\) calculated from Equation 21. The only difference is the terminal value of \(P\) which for this case is

\[
P(t + T) = \hat{P},
\]

where \(\hat{P}\) is already known from the Riccati equation 28. Since the computation of \(q(t)\) is cumbersome when \(P\) varies with time, an approximation for the easy computation of \(q\) is necessary. Similarly as in subsection IV-A, assuming that \(\hat{P} = 0\) then \(P = \text{const}\) and takes the value for time \(t + T\), e.g., \(P = \hat{P}\). With this simplification, the control signal \(u\) can be computed easily at every stage of control.
V. RESULTS AND DISCUSSION

In order to evaluate the tracking performance of the $H_\infty$ preview controller, the response of the system has been examined in the time and frequency domains for different types of reference signals. The response of the system with $H_\infty$ preview control has been compared with the response for $H_\infty$ feedback controller with 1.5 degrees-of-freedom (DOF) and $H_2$ preview controller [20]. The $H_\infty$ preview controller has been designed for the case when the reference signal is previewed for a fixed interval of time shorter than the total working time which is assumed to be long enough (sub-section IV-B). The preview time is chosen to be 1 second since longer times do not yield significant performance improvements.

A. Frequency Response

In order to compute the frequency response of the system with preview control, the Laplace transform $Q(s)$ of the preview part $q(t)$ of the control law of Equation 19 is required to be known. Using Equation 22 and recalling the definition of Laplace transform, where $R(s)$ is the Laplace transform of the reference signal $r(t)$ and $Q(s)$ is calculated as:

$$Q(s) = [Q_1(s) - Q_2(s)] R(s),$$

$$Q_1(s) = \exp[Ts] \left[s + A_{cl}^T + M\right]^{-1} \times \exp[\left(A_{cl}^T + M\right)T] PB_r,$$

$$Q_2(s) = \left[sI + A_{cl}^T + M\right]^{-1} PB_r.$$  

Figure 4 shows the gain and phase of the frequency response of the tracking system for $H_2$ preview control (solid line) and 1.5DOF $H_2$ feedback control (broken line). It can be noted that although the gain of the response is higher at high frequencies for 1.5DOF $H_2$ feedback control, the phase of the response for $H_2$ preview control is zero for frequencies up to 10 Hz. Zero phase response is desired in tracking systems since it is always desirable that the system responds to the reference input without delays. Figure 5 compares the gain and phase of the frequency response for $H_\infty$ preview control (solid line) and 1.5DOF $H_\infty$ feedback control (broken line). Similarly as for $H_2$ control, the gain of the response is higher for 1.5DOF $H_\infty$ feedback control but the phase of the response for $H_\infty$ preview control is close to zero for frequencies up to 1 Hz and is positive for the medium frequency range up to 10 Hz. This positive phase characteristics indicate that the system with $H_\infty$ preview control responds in advance to the reference input. Since in the medium frequency range the gain of the frequency response for $H_\infty$ preview control is low, the controller tries to compensate this deficiency by responding in advance with positive phase. Figure 6 shows the gain and phase of the frequency response for $H_\infty$ preview control (solid line) and $H_2$ preview control (broken line). It can be noted that the gain of the response is higher for $H_\infty$ preview control than for $H_2$ preview control. The phase response shows the zero-phase characteristics of $H_\infty$ preview control and the positive characteristics of $H_\infty$ preview control discussed before.

B. Time Response

The time response of the tracking system with $H_\infty$ preview control has been analyzed for sinusoidal and step reference inputs.

a) Sinusoidal Response

Figure 7 shows the time response of the system for a sinusoidal reference input of 0.5 Hz. Figure 7 (a) corresponds to 1.5DOF $H_\infty$ feedback control and Figure 7 (b) to $H_\infty$ preview control. In Figure 7 (a) it is noted that although the amplitude of the response of the system (solid line) is almost the same as the reference input (broken line), the system responds with delay and as it is shown in Figure 8, it has been found that although the step response for the system with 1.5DOF $H_\infty$ feedback control (broken line) and $H_\infty$ preview control (solid line) are almost the same, Figure 8 (a), the control signal $u$ is different for both controllers, Figure 8 (b). Preview control demands lower control signals and therefore requires less control energy to achieve the same tracking performance than 1.5DOF $H_\infty$ feedback control. Calculated results show that the control energy can be reduced even by 10% when using $H_\infty$ preview control.

b) Step Response

It is usually said that preview control improves the tracking performance of the system especially in situations where the signal to be tracked varies with time, and no significant improvement can be achieved for step reference signals for situations when the control action starts just when the reference signal is applied. However and as it is shown in Figure 8, it is clear that the tracking error is almost zero for the total working time.

VI. CONCLUSIONS

This paper has presented a novel design method of positioning/tracking systems based on $H_\infty$ preview control using the known future value of the reference input. Analysis of the frequency response shows that preview control improves the tracking performance by improving the phase response of the tracking system so that the system responds to the reference input without delay. The step response of the tracking system shows that $H_\infty$ preview control requires less control energy than 1.5DOF $H_\infty$ feedback control to achieve the same positioning performance.

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Fig. 4. Frequency response of $H_2$ preview control

Fig. 5. Frequency response of $H_\infty$ preview control

Fig. 6. Frequency response of $H_2$ and $H_\infty$ preview control
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REFERENCES


