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Guidance of Nonlinear Nonminimum-Phase Dynamic Systems

Primary

Performance Report

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Summary

The research work has advanced the inversion-based guidance theory for:

- systems with non-hyperbolic internal dynamics;
- systems with parameter jumps; and
- systems where a redesign of the output trajectory is desired.

Non-hyperbolic Internal Dynamics

A technique to achieve output tracking for nonminimum phase linear systems with non-hyperbolic and near non-hyperbolic internal dynamics was developed [1]. This approach integrated stable inversion techniques, that achieve exact-tracking, with approximation techniques, that modify the internal dynamics to achieve desirable performance. Such modification of the internal dynamics was used (a) to remove non-hyperbolicity which is an obstruction to applying stable inversion techniques and (b) to reduce large preactuation times needed to apply stable inversion for near non-hyperbolic cases. The method was applied to an example helicopter hover control problem with near non-hyperbolic internal dynamics for illustrating the trade-off between exact tracking and reduction of preactuation time.

Future work will extend these results to guidance of nonlinear nonhyperbolic systems.

Systems with Parameter Jumps

The exact output tracking problem for systems with parameter jumps was considered [2]. Necessary and sufficient conditions were derived for the elimination of switching-introduced output transient. While previous works had studied this problem by developing a regulator that maintains exact tracking through parameter jumps (switches), such techniques are, however, only applicable to minimum-phase systems. In contrast, our approach is also applicable to nonminimum-phase systems and leads to bounded but possibly non-causal solutions. In addition, for the case when the reference trajectories are generated by an exosystem, we developed an exact-tracking controller which could be written in a feedback form. As in standard regulator theory, we also obtained a linear map from the states of the exosystem to the desired system state, which was defined via a matrix differential equation. The

constant solution of this differential equation provided asymptotic tracking, and coincided with the feedback law used in standard regulator theory. Future work will extend these results to nonlinear systems and generalize these results to hybrid systems.

Output Trajectory Redesign

We studied the optimal redesign of output trajectory for linear invertible systems [3, 4]. The specified output trajectory uniquely determines the required input and state trajectories, that are found through inversion. These input-state trajectories exactly track the desired output, however, they might not meet acceptable performance requirements. For example, the required inputs might cause actuator-saturation during an exact tracking maneuver (as in the flight control of conventional take-off and landing aircraft). In such situations, a compromise is desired between the tracking requirement and other goals like reduction of internal vibrations and prevention of actuator saturation – i.e., the desired output trajectory needs to be redesigned.

We posed the trajectory redesign problem as an optimization of a general quadratic cost function, and solved it in the context of linear systems.

Future work will be aimed at extending these results to the nonlinear case and at developing algorithms for practical implementation.

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Appendix

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FUNDING

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TEACHING EXPERIENCE

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JOURNAL PUBLICATIONS

- E.A. Bailey, A.W. Dutton, M. Mattingly, S. Devasia and R.B. Roemer
"A Comparison of Reduced-Order Modeling Techniques for Application in Hyperthermia Control and Estimation" Submitted to International Journal of Hyperthermia, Oct., 1996.
- S. Devasia "Output Tracking for Systems with Non-Hyperbolic and Near Non-Hyperbolic Internal Dynamics: Helicopter Hover Control" Submitted to AIAA Journal of Guidance, Control, and Dynamics, Sept., 1996.
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Output Tracking for Systems with Non-Hyperbolic and Near Non-Hyperbolic Internal Dynamics: Helicopter Hover Control *

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Abstract - A technique to achieve output tracking for nonminimum phase linear systems with non-hyperbolic and near non-hyperbolic internal dynamics is presented. This approach integrates stable inversion techniques, that achieve exact-tracking, with approximation techniques, that modify the internal dynamics to achieve desirable performance. Such modification of the internal dynamics is used (a) to remove non-hyperbolicity which is an obstruction to applying stable inversion techniques and (b) to reduce large preactuation times needed to apply stable inversion for near non-hyperbolic cases. The method is applied to an example helicopter hover control problem with near non-hyperbolic internal dynamics for illustrating the trade-off between exact tracking and reduction of preactuation time.

1 Introduction

Precision output tracking controllers are needed to meet increasingly stringent performance requirements in applications like flexible structures, aircraft and air traffic control, robotics, and manufacturing systems. While perfect tracking of minimum phase systems is relatively easy to achieve, output tracking of nonminimum phase systems tends to be more challenging due to fundamental limitations on transient tracking performance [1]. This *poor* transient performance has been mitigated by using preactuation in the stable-inversion based approaches for nonminimum phase systems [2, 3, 4, 5]. However, the required preactuation time (during which *most* of the preactuation control effort is required) is large if the zeros of a linear system that lie on the open right half of the complex plane are close to the imaginary axis. In the limiting case, with the zeros on the imaginary axis (non-hyperbolic internal dynamics), presently available inversion-based techniques fail because the preactuation time

needed becomes infinite. In this paper we present a design technique for output tracking of linear non-minimum phase systems, which have non-hyperbolic and near non-hyperbolic non-minimum phase internal dynamics. This technique is then applied to an example helicopter hover control and simulation results are presented.

Output tracking has a long history marked by the development of regulator theory for linear systems by Francis and Wonham [6] and generalized to the nonlinear case by Byrnes and Isidori [7]. These approaches asymptotically track an output from a class of exosystem-generated outputs. Further, the Byrnes-Isidori regulator has been extended in [8, 9] and computational issues have been studied in [10, 11]. Although nonlinear regulator design is computationally difficult, the linear regulator is easily designed by solving a manageable set of linear equations. A problem, however, with the regulator approach is that the exosystem states are often switched to describe the desired output – this leads to transient tracking-errors after the switching instants. Such switching caused transient errors can be avoided by using inversion-based approaches to output tracking [4, 12]. Thus, it is advantageous to use inversion-based output tracking when precision tracking of a particular output trajectory is required.

Inversion, which is key to our approach, was restricted to causal inverses of minimum phase systems in the early works by Silverman and Hirschorn (e.g., [13, 14]) because they lead to unbounded inverses in the nonminimum phase case. Di Benedetto and Lucibello [15] considered the inversion of time varying nonminimum phase systems with a choice of the system's initial conditions. Instead of choosing initial conditions, preactuation was used by noncausal stable inversion techniques developed in [2, 3, 4, 16, 5]. Such noncausal inverses, which require preactuation, have been successfully applied to the output tracking of flexible

structures [17, 18] and aircraft and air traffic control [19, 20]. However, the fundamental limitation of presently available inversion- schemes is that they fail if the internal dynamics is non-hyperbolic. Even when the internal dynamics is hyperbolic, if the right-half-plane zeros of the system are close to the imaginary axis (the near non-hyperbolic case) then the required preactuation time tends to become unacceptably large. In summary, output tracking remains a challenge for nonminimum phase systems with non-hyperbolic or near non-hyperbolic internal dynamics.

There are several approximation based output tracking techniques, where the central philosophy is to replace the internal dynamics with a dynamics that provides satisfactory behavior, and then to develop the controller based on the altered system [21, 22, 23]. The technique most relevant to this paper is developed by Gopalswamy and Hedrick [23] – where trajectory modifications are considered to stabilize the internal dynamics. This technique, however, requires hyperbolicity of the internal dynamics for computational purposes. The development of computational techniques for stable inversion (e.g., [16]) motivates the present integration of the stable inversion scheme with approximation techniques - especially for systems with non-hyperbolic internal dynamics where the existing stable-inversion techniques fail. However, instead of stabilizing the unstable internal dynamics, we only aim to modify the non-hyperbolic behavior with a *small* perturbation of the internal dynamics. Additionally, in nonminimum phase systems with near non-hyperbolic internal dynamics the present approach allows a tradeoff between the precision tracking requirement and the amount of preactuation time, needed to apply the stable inversion based output tracking technique.

The approximate inversion-based technique is developed in Section 2 and the technique is applied to a helicopter hover control example in Section 3, where simulation results are

discussed. Our conclusions are in Section 4.

2 Stable Inversion

2.1 Inversion-Based Output Tracking Scheme

Here we describe how the inversion approach is used to develop output tracking controllers.

Consider a linear system described by

$$\begin{aligned} \dot{x}(t) &= A x(t) + B u(t) \\ y(t) &= C x(t) \end{aligned} \tag{1}$$

which has the same number of inputs as outputs, $u(t), y(t) \in \mathbb{R}^p$, and $x(t) \in \mathbb{R}^n$. Let $y_d(\cdot)$ be the desired output trajectory to be tracked. Then in the inversion-based approach we, first, find a nominal input-state trajectory, $[u_{ff}(\cdot), x_{ref}(\cdot)]$ that satisfies the system equations (1) and yields the desired output exactly, i.e.,

$$\left. \begin{aligned} \dot{x}_{ref}(t) &= A x_{ref}(t) + B u_{ff}(t) \\ y_d(t) &= C x_{ref}(t) \end{aligned} \right\} \forall t \in (-\infty, \infty) \tag{2}$$

and, second, we stabilize the exact-output yielding state trajectory, $x_{ref}(\cdot)$, by using state feedback (see Figure 1). Thus $x(t) \rightarrow x_{ref}(t)$ and $y(t) \rightarrow y_d(t)$ as $t \rightarrow \infty$ and output tracking is achieved. It is noted that in this output tracking scheme, the reference state trajectory $x_{ref}(\cdot)$ and the feedforward input $u_{ff}(\cdot)$ are computed off-line. While stabilization of the reference state trajectory can be easily achieved through standard techniques [24] like state feedback of the form $K[x(t) - x_{ref}(t)]$, the main challenge is to find the inverse input-state trajectory $[u_{ff}(\cdot), x_{ref}(\cdot)]$ – especially for systems with nonminimum phase dynamics. This

paper addresses the off-line computation of the inverse input-state trajectory for a given desired trajectory, $y_d(\cdot)$.

2.2 The Internal Dynamics

In this subsection, it is shown that finding the inverse input-state trajectory is equivalent to finding bounded solutions to the system's internal dynamics. Let the linear system (1) have a well defined vector relative degree, $r := [r_1, r_2, \dots, r_p]$. Then the output's derivatives are given as [25]

$$\frac{d^{r_k}}{dt^{r_k}} y_k = C_k A^{r_k} x + C_k A^{r_k-1} B u \quad (3)$$

where C_k is the k^{th} row of C , and $1 \leq k \leq p$. In vector notation let equation (3) be rewritten as

$$y^{(r)}(t) = A_x x(t) + B_y u(t) \quad (4)$$

where

$$y^{(r)} := \left[\frac{d^{r_1} y_1}{dt^{r_1}} \quad \frac{d^{r_2} y_2}{dt^{r_2}} \quad \dots \quad \frac{d^{r_p} y_p}{dt^{r_p}} \right]^T$$

$$A_x := \begin{bmatrix} C_1 A^{r_1} \\ C_2 A^{r_2} \\ \vdots \\ C_p A^{r_p} \end{bmatrix}; \quad B_y := \begin{bmatrix} C_1 A^{r_1-1} B \\ C_2 A^{r_2-1} B \\ \vdots \\ C_p A^{r_p-1} B \end{bmatrix},$$

and B_y is invertible because of the well-defined relative degree assumption. Equation (4) motivates the choice of the control law of the form

$$u_{ff}(t) = B_y^{-1} [y_d^{(r)}(t) - A_x x(t)] \quad (5)$$

for all $t \in (-\infty, \infty)$. Substituting this control law in equation (4), it is seen that exact tracking is maintained, i.e.,

$$y^{(r)}(t) = y_d^{(r)}(t).$$

To study the effect of this control law consider a change of coordinates T such that [25]

$$\begin{bmatrix} \zeta(t) \\ \eta(t) \end{bmatrix} = T x(t)$$

where $\zeta(t)$ consists of the output and its time-derivatives

$$\zeta(t) := \left[y_1, \dot{y}_1, \dots, \frac{d^{r_1-1}}{dt^{r_1-1}} y_1, y_2, \dot{y}_2, \dots, \frac{d^{r_2-1}}{dt^{r_2-1}} y_2, \dots, y_p, \dot{y}_p, \dots, \frac{d^{r_p-1}}{dt^{r_p-1}} y_p \right]'$$

The system equation (1) can then be re-written in the new-coordinates as

$$\dot{\zeta}(t) = \hat{A}_1 \zeta + \hat{A}_2 \eta + \hat{B}_1 u \quad (6)$$

$$\dot{\eta}(t) = \hat{A}_3 \zeta + \hat{A}_4 \eta + \hat{B}_2 u \quad (7)$$

where

$$\hat{A} := T^{-1} A T := \begin{bmatrix} \hat{A}_1 & \hat{A}_2 \\ \hat{A}_3 & \hat{A}_4 \end{bmatrix}; \quad \text{and} \quad \hat{B} := \begin{bmatrix} \hat{B}_1 \\ \hat{B}_2 \end{bmatrix} = T^{-1} B$$

In the new co-ordinates, the control law for maintaining exact tracking (Equation (5)) can be written as

$$u(t) = B_y^{-1} \left[y_d^{(r)}(t) - A_\zeta \zeta_d(t) - A_\eta \eta(t) \right] \quad (8)$$

where

$$\begin{bmatrix} A_\zeta \\ A_\eta \end{bmatrix} := A_x T^{-1}.$$

Note that the desired $\zeta(\cdot)$ is known when the desired output trajectory $y_d(\cdot)$ and the output's time derivatives are specified. This desired $\zeta(\cdot)$ is defined as $\zeta_d(\cdot)$. Since the control law was

chosen such that exact tracking is maintained, $y^{(r)}(t) = y_d^{(r)}(t)$ we also have $\dot{\zeta}(t) = \dot{\zeta}_d(t)$, and Equations (6) and (7) become

$$\dot{\zeta}(t) = \dot{\zeta}_d(t) \quad (9)$$

$$\dot{\eta}(t) = \hat{A}_3\zeta + \hat{A}_4\eta + \hat{B}_2B_y^{-1} [y_d^{(r)}(t) - A_\zeta\zeta_d(t) - A_\eta\eta(t)]. \quad (10)$$

This is the inverse system, and in particular, Equation (10) is the internal dynamics. Solving the internal dynamics is key to finding the inverse input-state trajectories. If a bounded solution, $\eta_d(\cdot)$, to the internal dynamics (10) can be found then the feedforward input can be found through equation (8) as

$$u_{ff}(t) = B_y^{-1} [y_d^{(r)}(t) - A_\zeta\zeta_d(t) - A_\eta\eta_d(t)] \quad (11)$$

and the reference trajectory can be found as

$$x_{ref}(t) = T^{-1} \begin{bmatrix} \zeta_d(t) \\ \eta_d(t) \end{bmatrix}.$$

Thus a bounded solution to the internal dynamics (10) is required to find the inverse and to apply the output tracking scheme shown in Figure 1.

2.3 Modified Internal Dynamics

Standard inversion schemes [13, 14] that integrate (forward in time) the internal dynamics (10) lead to unbounded solutions since the internal dynamics is unstable for nonminimum phase systems. Noncausal inversion (e.g., [4]) leads to bounded but noncausal solution to the internal dynamics. Such stable-inversion techniques are, however, not applicable to systems with non-hyperbolic internal dynamics. In this subsection a compromise between

stable inversion and approximation based inversion schemes is proposed. The key is to modify the internal dynamics by giving up exact output tracking – enough to remove the non-hyperbolicity, and then to apply stable-inversion. The difference between the proposed technique and other approximation techniques is that the internal dynamics is perturbed only to remove the non-hyperbolicity, and not to stabilize the entire internal dynamics.

To change the non-hyperbolicity of the internal dynamics an extra term, $v(t)$, is added to the control law (8) as follows

$$u_{ff}(t) = B_y^{-1} \left[y_d^{(r)}(t) - A_\zeta \zeta_d(t) - A_\eta \eta(t) + v(t) \right]. \quad (12)$$

With this modified control law the inverse system (Equations (9) and (10)) become

$$\frac{d}{dt} \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} = \hat{S} \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} + G_y Y_d(t) + G_v v(t) \quad (13)$$

where $e_\zeta(t) := \zeta(t) - \zeta_d(t)$ is the error in the output and the output's derivatives,

$$\hat{S} = \begin{bmatrix} 0 & 0 \\ \hat{A}_3 & (\hat{A}_4 + \hat{B}_2 B_y^{-1} A_\eta) \end{bmatrix}, \quad G_v = \begin{bmatrix} \hat{B}_1 B_y^{-1} \\ \hat{B}_2 B_y^{-1} \end{bmatrix},$$

$$G_y = \begin{bmatrix} 0 & 0 \\ (\hat{A}_3 - \hat{B}_2 B_y^{-1} A_\zeta) & \hat{B}_2 B_y^{-1} \end{bmatrix}, \quad \text{and } Y_d(t) = \begin{bmatrix} \zeta_d(t) \\ y_d^{(r)}(t) \end{bmatrix}$$

Assuming that the original system (A, B) is controllable, we also have (\hat{S}, G_v) controllable and hence there exists a feedback of the form

$$v(t) = F \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} \quad (14)$$

such that the modified inverse system (13) is hyperbolic – i.e., all poles on the imaginary axis are moved. Note that this change to an hyperbolic system can be achieved through arbitrarily

small F since non-hyperbolicity is not structurally stable property. The hyperbolic system

$$\begin{aligned} \frac{d}{dt} \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} &= (S + G_v F) \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} + G_y Y_d(t) \\ &:= S \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} + G_y Y_d(t) \end{aligned} \quad (15)$$

is the modified inverse system. This modification of the internal dynamics can also be used to move unstable poles of the inverse system that may be close to the imaginary axis for reducing the required preactuation time. Next, stable inversion of the modified inverse system is carried out [4].

2.4 Computation of the Inverse

We begin by decoupling the modified internal dynamics (15) into stable (z_s) and unstable (z_u) subsystems. Since the modified internal dynamics is hyperbolic, there exists a decoupling transformation U such that the modified inverse system (15) can be written as

$$\begin{aligned} \dot{z}_s(t) &= S_s z_s(t) + G_s Y_d(t) \\ \dot{z}_u(t) &= S_u z_u(t) + G_u Y_d(t) \end{aligned} \quad (16)$$

where

$$z(t) := \begin{bmatrix} z_s(t) \\ z_u(t) \end{bmatrix} = U \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix}. \quad (17)$$

To find bounded solutions to the unstable inverse systems, the boundary conditions that $z_s(-\infty) = 0$ and $z_u(\infty) = 0$ are applied to Equation (16). This leads to unique bounded solutions to the modified internal dynamics by flowing the stable subsystem forward in time

and flowing the unstable system backward in time – as

$$z_{s,d}(t) = \int_{-\infty}^t e^{S_s(t-\tau)} G_u Y_d(\tau) d\tau \quad \forall t \in (-\infty, \infty), \quad (18)$$

$$z_{u,d}(t) = - \int_t^{\infty} e^{S_u(t-\tau)} G_u Y_d(\tau) d\tau \quad \forall t \in (-\infty, \infty).$$

This completes the technique. To summarize, the bounded solution (18) is used to find the reference state trajectory as $x_{ref}(t) = T^{-1}U^{-1}z_d(t)$, and to find the feedforward input, $u_{ff}(\cdot)$ from equation (12). This inverse, $[u_{ff}(\cdot), x_{ref}(\cdot)]$, is then used in the control scheme shown in Figure 1 to obtain output tracking.

2.5 Preactuation Time and Unstable Poles of Inverse System

The connection between the amount of preactuation time required to apply the inversion-based feedforward input and the unstable poles of the modified inverse is established in the following Lemma. **Lemma** Let

1. the support of $Y_d(\cdot)$ be contained in $[t_0, \infty)$ for some t_0 ,
2. all the unstable poles of internal dynamics represented by the eigenvalues of S_u lie to the right, in the complex plane, of the line $\text{Re}(s) = \alpha$ for some positive α , and
3. $\|G_u Y_d(\cdot)\|_{\infty} < \beta$.

Then there exists M such that $\|u_{ff}(t)\|_{\infty} < M e^{\alpha(t-t_0)}$ for all time before the start of the maneuver, $t < t_0$.

Proof: From Condition 2 of the Lemma, there exists a positive constant M_{S_u} such that

$$\|e^{S_u(t-\tau)}\|_{\infty} < M_{S_u} e^{\alpha(t-\tau)} \quad \forall t < \tau. \quad (19)$$

Then for all $t < t_0$,

$$\begin{aligned}
\|u_{ff}(t)\|_\infty &= \|B_y^{-1} [y_d^{(r)}(t) - A_\zeta \zeta_d(t) - A_\eta \eta(t) + v(t)]\|_\infty \text{ from Equation (12)} \\
&= \|B_y^{-1} [-A_\eta \eta(t) + v(t)]\|_\infty \text{ from Condition 1 of the Lemma} \\
&= \left\| \left(\begin{bmatrix} 0 & 0 \\ 0 & -B_y^{-1} A_\eta \end{bmatrix} + F \right) \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} \right\|_\infty \text{ from Equation (14)} \\
&:= \left\| A_U \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} \right\|_\infty \\
&\leq \|A_U\|_\infty \left\| \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} \right\|_\infty \\
&\leq \|A_U\|_\infty \|U^{-1}\|_\infty \left\| \begin{bmatrix} z_s(t) \\ z_u(t) \end{bmatrix} \right\|_\infty \text{ from Equation (17)} \\
&= \|A_U\|_\infty \|U^{-1}\|_\infty \|z_u(t)\|_\infty \text{ since } z_s(t) = 0 \text{ for all } t < t_0 \\
&= \|A_U\|_\infty \|U^{-1}\|_\infty \left\| \int_t^\infty e^{S_u(t-\tau)} G_u Y_d(\tau) d\tau \right\|_\infty \text{ from Equation (18)} \\
&= \|A_U\|_\infty \|U^{-1}\|_\infty \left\| \int_{t_0}^\infty e^{S_u(t-\tau)} G_u Y_d(\tau) d\tau \right\|_\infty \text{ from Condition 1 of Lemma} \\
&< \beta M_{S_u} \|A_U\|_\infty \|U^{-1}\|_\infty \int_{t_0}^\infty e^{\alpha(t-\tau)} d\tau
\end{aligned}$$

from Equation (19) and Condition 3 of Lemma. Integrating the above expression we get

$$\begin{aligned}
\|u_{ff}(t)\|_\infty &< \frac{\beta M_{S_u}}{\alpha} \|A_U\|_\infty \|U^{-1}\|_\infty e^{\alpha(t-t_0)} \\
&:= M e^{\alpha(t-t_0)},
\end{aligned}$$

which concludes the proof. ■

The above Lemma states that the preactuation input tends to zero exponentially, as we go back in time from the start of the maneuver at t_0 . The rate at which the preactuation

becomes zero can be increased by moving the unstable poles of the modified inverse away from the imaginary axis – at the expense of exact output tracking. The trade-off between exact-tracking of the desired output and reduction of the pre-actuation time is illustrated in the following example.

3 Example: Helicopter Hover Control

Here, we apply the output-tracking technique to the hover control of a Bell 205 Helicopter, which has near non-hyperbolic unstable internal dynamics. We consider one of the cases studied previously in [26], wherein the aircraft dynamics was trimmed at a nominal 5° pitch attitude, with a mid-range weight, a mid-position center of gravity and operating in-ground effect at near sea level. The linearized model is given as [26, 27]

$$\dot{x} = Ax + Bu \tag{20}$$

where

$$A = \begin{bmatrix} 0 & 0.03 & 0.18 & -0.01 & -0.42 & 0.08 & -9.81 & 0 \\ -0.10 & -0.39 & 0.09 & -0.10 & -0.72 & 0.68 & 0 & 0 \\ 0.01 & -0.01 & -0.19 & 0 & 0.23 & 0.04 & 0 & 0 \\ 0.02 & 0 & -0.41 & -0.05 & -0.27 & 0.27 & 0 & 9.81 \\ 0.03 & -0.02 & -0.88 & -0.04 & -0.57 & 0.14 & 0 & 0 \\ -0.01 & -0.02 & -0.06 & 0.07 & -0.32 & -0.71 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \tag{21}$$

$$B = \begin{bmatrix} 0.08 & 0.13 & 0 & 0 \\ -1.17 & 0.04 & 0 & 0.01 \\ 0 & -0.07 & 0 & 0.01 \\ -0.04 & 0 & 0.11 & 0.19 \\ -0.04 & 0 & 0.22 & 0.17 \\ 0.17 & 0 & 0.03 & -0.47 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad (22)$$

$$x = \begin{bmatrix} U \\ W \\ Q \\ V \\ P \\ R \\ \theta \\ \phi \end{bmatrix} = \begin{bmatrix} \text{forward velocity} \\ \text{vertical velocity} \\ \text{pitch rate} \\ \text{lateral velocity} \\ \text{roll rate} \\ \text{yaw rate} \\ \text{roll rate} \\ \text{pitch attitude} \\ \text{roll attitude} \end{bmatrix}, \quad (23)$$

and

$$u = \begin{bmatrix} \delta_C \\ \delta_B \\ \delta_A \\ \delta_P \end{bmatrix} = \begin{bmatrix} \text{collective} \\ \text{longitudinal cyclic} \\ \text{lateral cyclic} \\ \text{tail rotor collective} \end{bmatrix}. \quad (24)$$

It is noted that the helicopter's actual dynamic behavior differs because of modeling errors like nonlinearities and unmodeled dynamics. In output tracking control schemes that depend on the model, such modeling errors need to be corrected through feedback in the control scheme (see Figure 1). In particular, modeling errors can be compensated by robust stabilization of the reference state-trajectory, see for example [26]. The goal of the present paper is to develop inversion-based feedforward and reference state trajectories for use in the control scheme shown in Figure 1. In the following, we apply the inversion technique to control the helicopters forward, lateral and vertical velocities and its yaw rate. The forward velocity and the yaw rate are to be kept at zero and the desired profiles of lateral and vertical velocities and accelerations are as shown in Figures 2 and 3.

3.1 Internal Dynamics

To find the internal dynamics we begin with a change in the co-ordinates. Let, ζ be defined as the outputs

$$\zeta(t) := \begin{bmatrix} U(t) \\ W(t) \\ V(t) \\ R(t) \end{bmatrix} \quad (25)$$

and let η be the remaining states,

$$\eta(t) := \begin{bmatrix} Q(t) \\ \theta(t) \\ P(t) \\ \phi(t) \end{bmatrix} \quad (26)$$

In the (ζ, η) co-ordinate system, given by

$$\begin{bmatrix} \zeta(t) \\ \eta(t) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} x(t) \quad (27)$$

$$:= Tx(t),$$

the system equations can be re-written as

$$\begin{bmatrix} \dot{\zeta}(t) \\ \dot{\eta}(t) \end{bmatrix} = TAT^{-1} \begin{bmatrix} \zeta(t) \\ \eta(t) \end{bmatrix} + TBu(t)$$

$$:= \begin{bmatrix} A_1 & A_2 \\ A_3 & A_4 \end{bmatrix} \begin{bmatrix} \zeta(t) \\ \eta(t) \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} u(t). \quad (28)$$

Given a desired output trajectory and the desired output's time derivatives, $[\zeta_d(\cdot), \dot{\zeta}_d(\cdot)]$, the exact output tracking control law (see Section 2.4) is found from equation (28) as

$$u_{ff}(t) = B_1^{-1} [\dot{\zeta}_d(t) - A_1\zeta_d(t) - A_2\eta(t)] \quad (29)$$

With this control law the inverse system becomes (from equation (28))

$$\dot{\zeta}(t) = \dot{\zeta}_d(t) \quad (30)$$

$$\dot{\eta}(t) = A_4\eta(t) + A_3\zeta(t) + B_2u(t)$$

$$\begin{aligned}
&= [A_4 - B_2 B_1^{-1} A_2] \eta(t) + B_2 B_1^{-1} [\dot{\zeta}_d(t) - A_1 \zeta_d(t)] \\
&:= A_\eta \eta(t) + B_2 B_1^{-1} [\dot{\zeta}_d(t) - A_1 \zeta_d(t)].
\end{aligned} \tag{31}$$

The problem is solved by finding a bounded solution to the internal dynamics (31). However, the bounded solution found through stable-inversion is noncausal and could require a large preactuation time if the poles of the internal dynamics are unstable and lie close to the imaginary axis in the complex plane. For this particular example, there are two such complex conjugate poles near the imaginary axis, $0.0425 \pm 4.3055i$. We modify the exact-tracking control law (29) to shift these poles away from the imaginary axis to $2 \pm 4.3055i$. This is described next.

3.2 Modified Inverse System

Following the approach described in Sections 2.3, we modify the internal dynamics by adding a term $v(t)$ to the control law (29) to obtain

$$u_{ff}(t) = B_1^{-1} [\dot{\zeta}_d(t) - A_1 \zeta_d(t) - A_2 \eta_d(t)] + v(t). \tag{32}$$

Substituting this control law into Equations 30 and 31, the modified inverse system is obtained as

$$\begin{aligned}
\begin{bmatrix} \dot{e}_\zeta(t) \\ \dot{\eta}(t) \end{bmatrix} &= \begin{bmatrix} 0 & 0 \\ A_3 & A_\eta \end{bmatrix} \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} v(t) + \\
&\quad \begin{bmatrix} 0 & 0 \\ (A_3 - B_2 B_1^{-1} A_1) & B_2 B_1^{-1} \end{bmatrix} \begin{bmatrix} \zeta_d(t) \\ \dot{\zeta}_d(t) \end{bmatrix}
\end{aligned}$$

$$:= \hat{S} \begin{bmatrix} e_\zeta(t) \\ \eta(t) \end{bmatrix} + G_v v(t) + G_y Y_d(t). \quad (33)$$

where $e_\zeta(t) := \zeta(t) - \zeta_d(t)$. The poles of the inverse system can be moved to any desired location by using the control $v(t)$ because (\hat{S}, G_v) is controllable. However, such modifications, aimed at reducing preactuation time, will also lead to a loss of precision in output tracking. This tradeoff between the reduction of preactuation time and the loss of precision in tracking is illustrated through simulation.

3.3 Simulation Results and Discussion

Two sets of simulations were performed. First, stable inversion was applied to the original system which lead to exact output-tracking inverse input-state trajectories. Second, simulations were performed when the unstable poles of the inverse system are moved from $0.0425 \pm 4.3055i$ to $2 \pm 4.3055i$ for reducing the amount of preactuation time required. Further, the inverse system also has four poles at the origin - corresponding to four pure integrators for $(e_\zeta(\cdot))$ dynamics - which were moved to $-1, -2, -3$ and -4 for stability of the numerical integration scheme.

Figures 2 and 3 show the desired output trajectories for the lateral and vertical motions (corresponding to unit displacements in the two directions), while the forward velocity and yaw rate were to be maintained at zero – the maneuver starts at time $t = 0$. Figures 4 and 5 show the output trajectories achieved by the inverse state-trajectory, $x_{ref}(\cdot)$, which is to be used as a reference trajectory in the feedback scheme shown in Figure 1. The corresponding feedforward inputs are shown in figures 6 and 7. Note here that the feedforward inputs

are non-zero before the start of the maneuver, i.e., time $t < 0$, and hence preactuation is required.

Figures 4 and 5 show that exact-output tracking reference state trajectories can be found, even when the internal dynamics is unstable, through the stable inversion approach. The stable-inversion technique yields bounded solutions to the unstable internal dynamics, i.e., the pitch and roll motions are bounded as shown in Figure 8. However, the feedforward input found through exact-inversion requires substantial preactuation time as shown in Figures 6 and 7, i.e., the preactuation remains non-zero for a significant time before the start of the maneuver at $t = 0$. Figure 9 shows that about 30 seconds of preactuation is needed to apply the inverse of the original system for output tracking – in contrast, modification of the internal dynamics reduces the preactuation needed from 30 seconds to 1 second (see Figure 9). As seen in Figures 4 and 5 the output trajectories are still tracked well by the modified inverse. Further, this substantial reduction in preactuation time is achieved with similar control efforts and with similar roll and pitch motions (see Figures 6-8). Thus the approach presented here, allows a trade-off between precision tracking and the amount of preactuation that is acceptable. Future work will generalize the results to nonlinear nonminimum phase systems with non-hyperbolic internal dynamics.

4 Conclusions

A technique to achieve output tracking for nonminimum phase linear systems with non-hyperbolic and near non-hyperbolic internal dynamics was presented. This approach is an integration of the stable inversion technique that aims at exact tracking with the approxi-

mation approach that modifies the internal dynamics to achieve desirable performance. The method was applied to an example helicopter hover control problem to illustrate the effects of modifying the internal dynamics. It was shown that substantial reduction in preactuation time is possible by giving up some of the precision in tracking – thus making the stable inversion approach viable for practical application.

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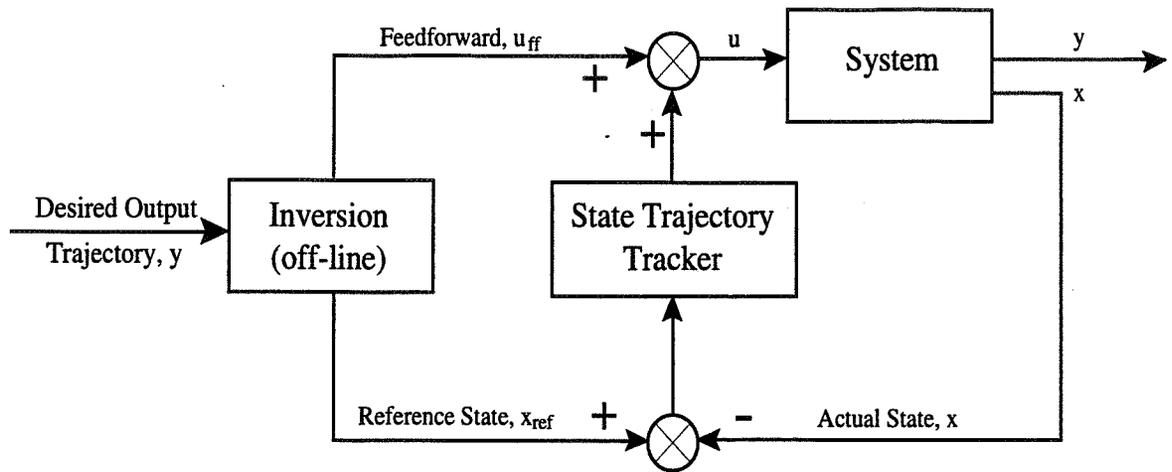


Figure 1. The Control Scheme

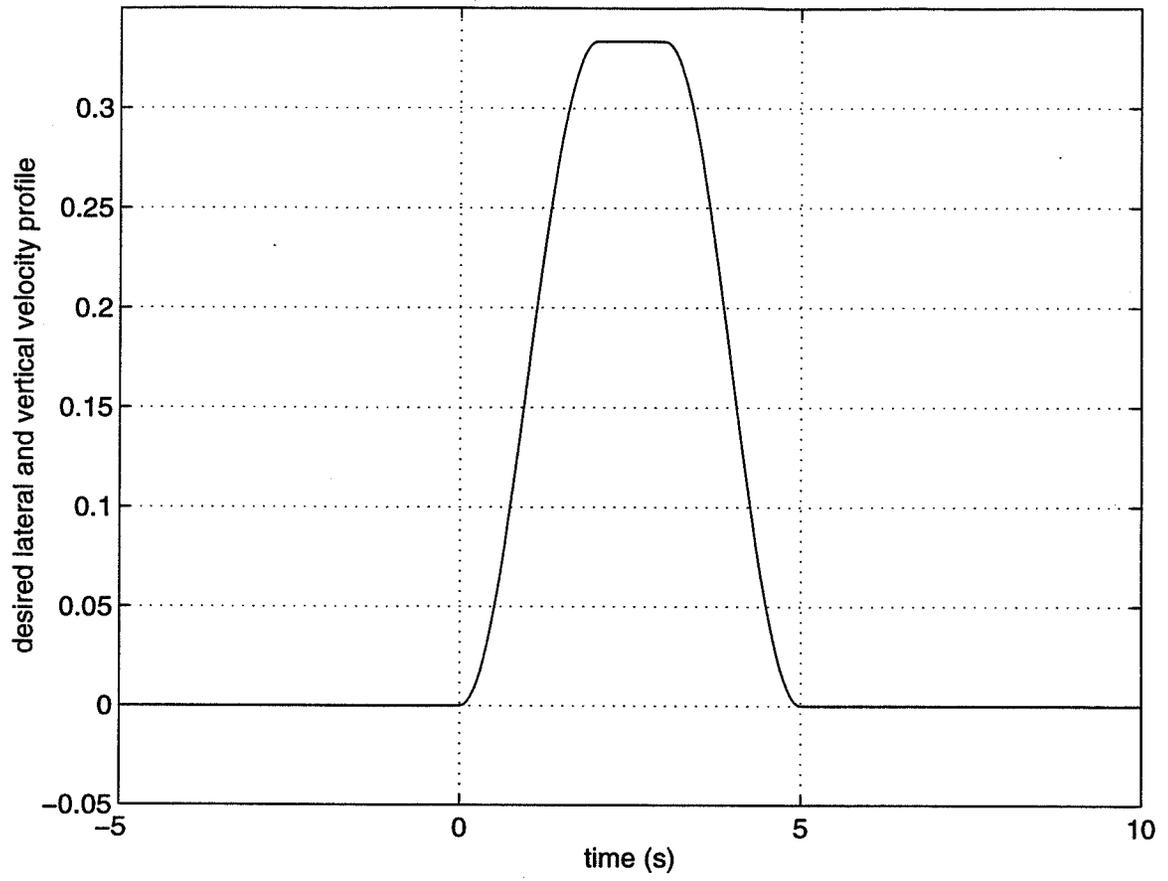


Figure 2. Desired Lateral and Vertical Velocity Profile.

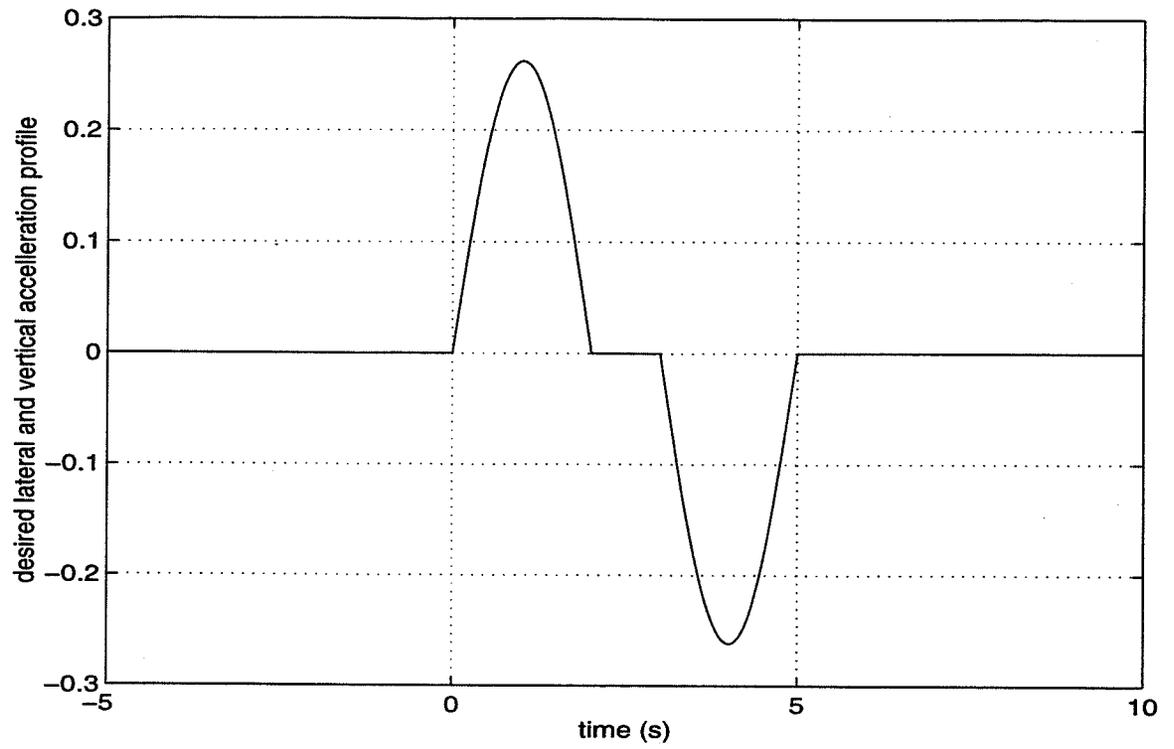


Figure 3. Desired Lateral and Vertical Acceleration Profile.

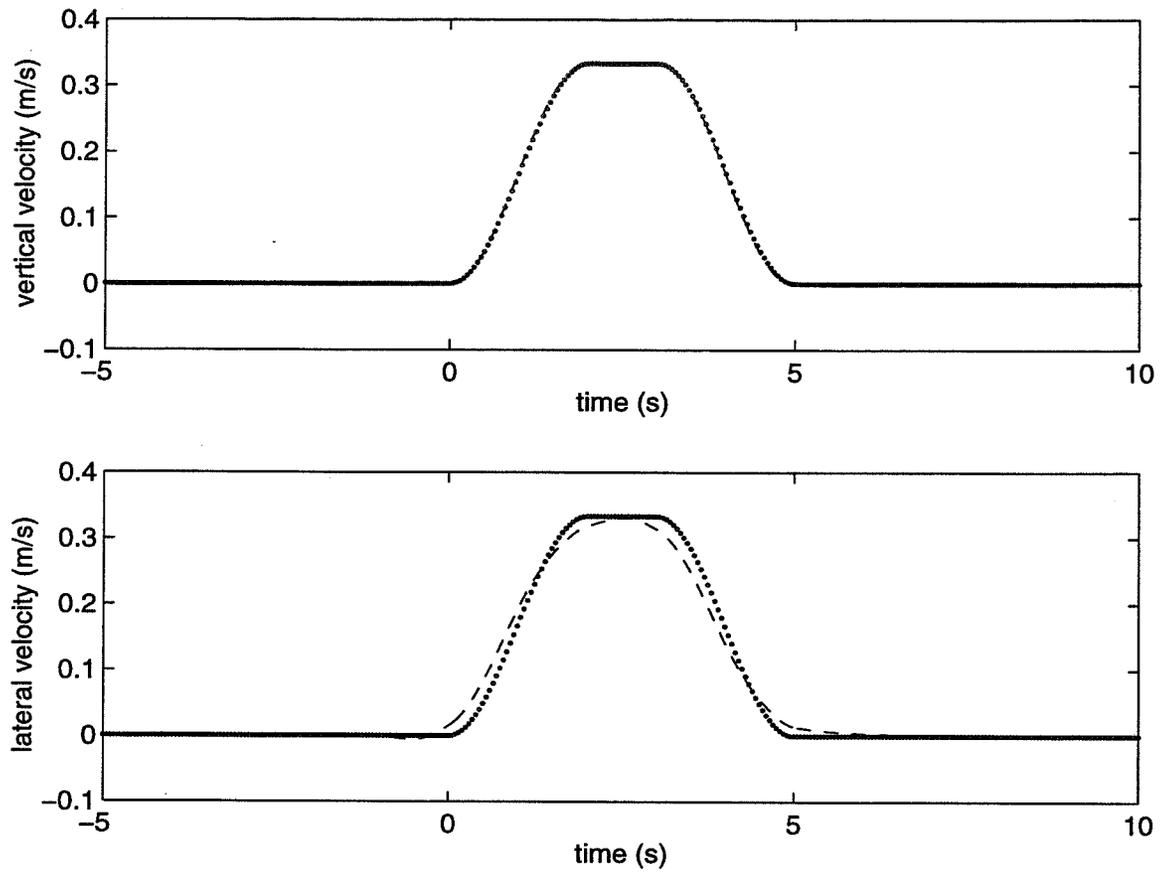


Figure 4. Lateral and Vertical Velocity achieved by the Inverse Reference State Trajectory. The dotted line is for the exact-tracking case without modification of the internal dynamics and the dashed line is with modification.

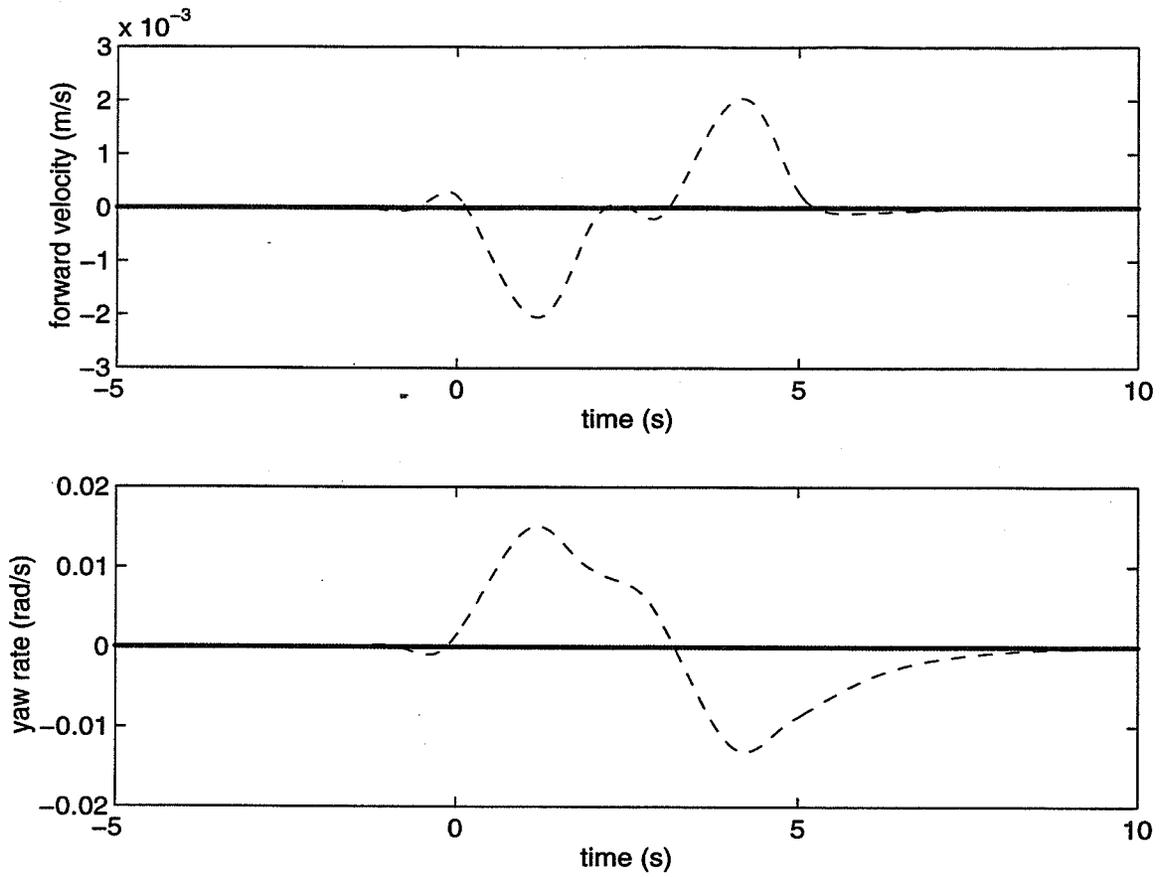


Figure 5. Forward Velocity and Yaw Rate achieved by the Inverse Reference State Trajectory – the desired value is zero. The dotted line is for the exact-tracking case without modification of the internal dynamics and the dashed line is with modification.

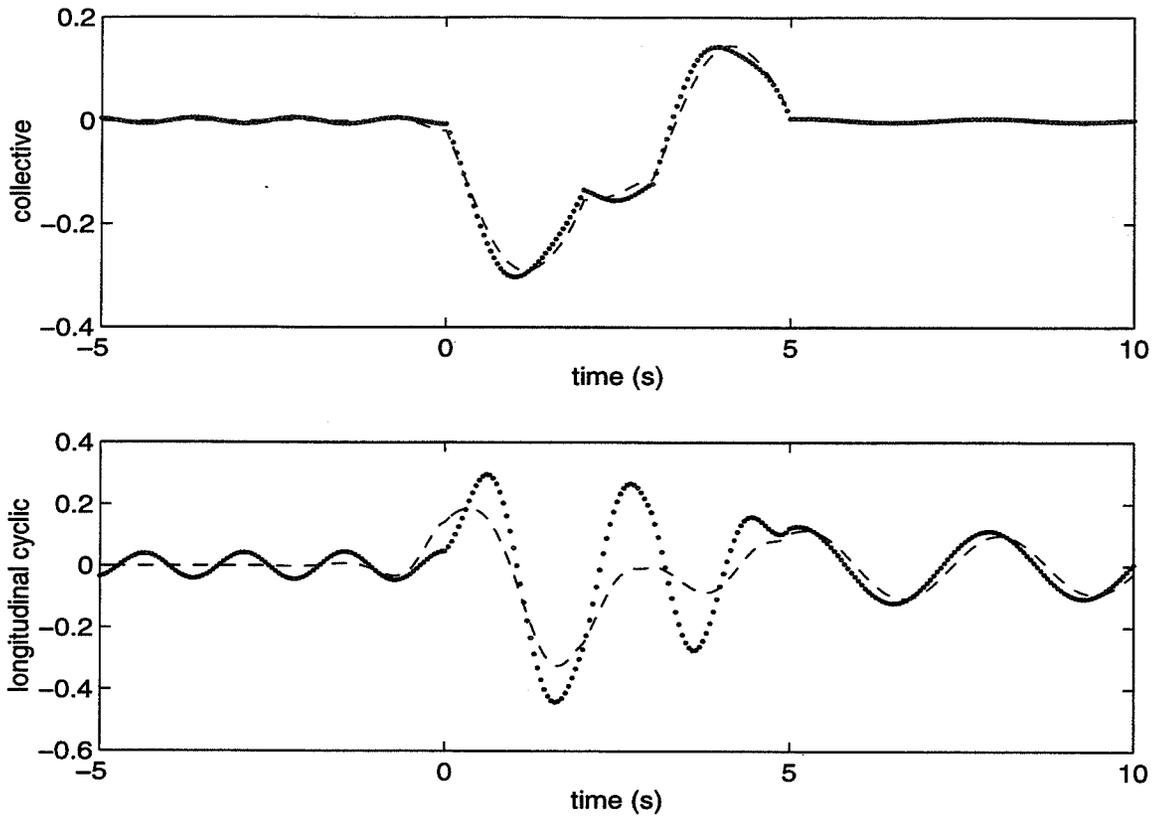


Figure 6. Feedforward Inputs. Dotted line is without modification of internal dynamics and the dashed line is with modification.

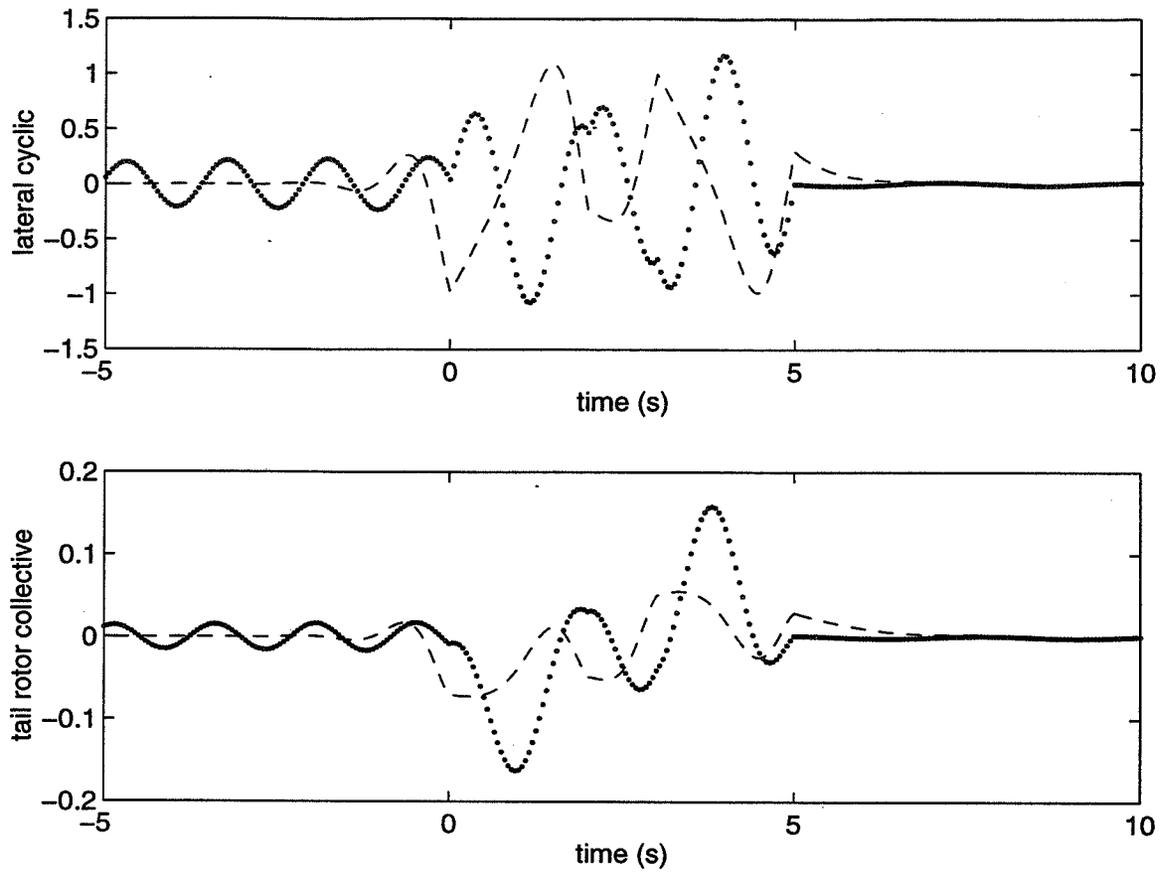


Figure 7. Feedforward Inputs. Dotted line is without modification of internal dynamics and the dashed line is with modification.

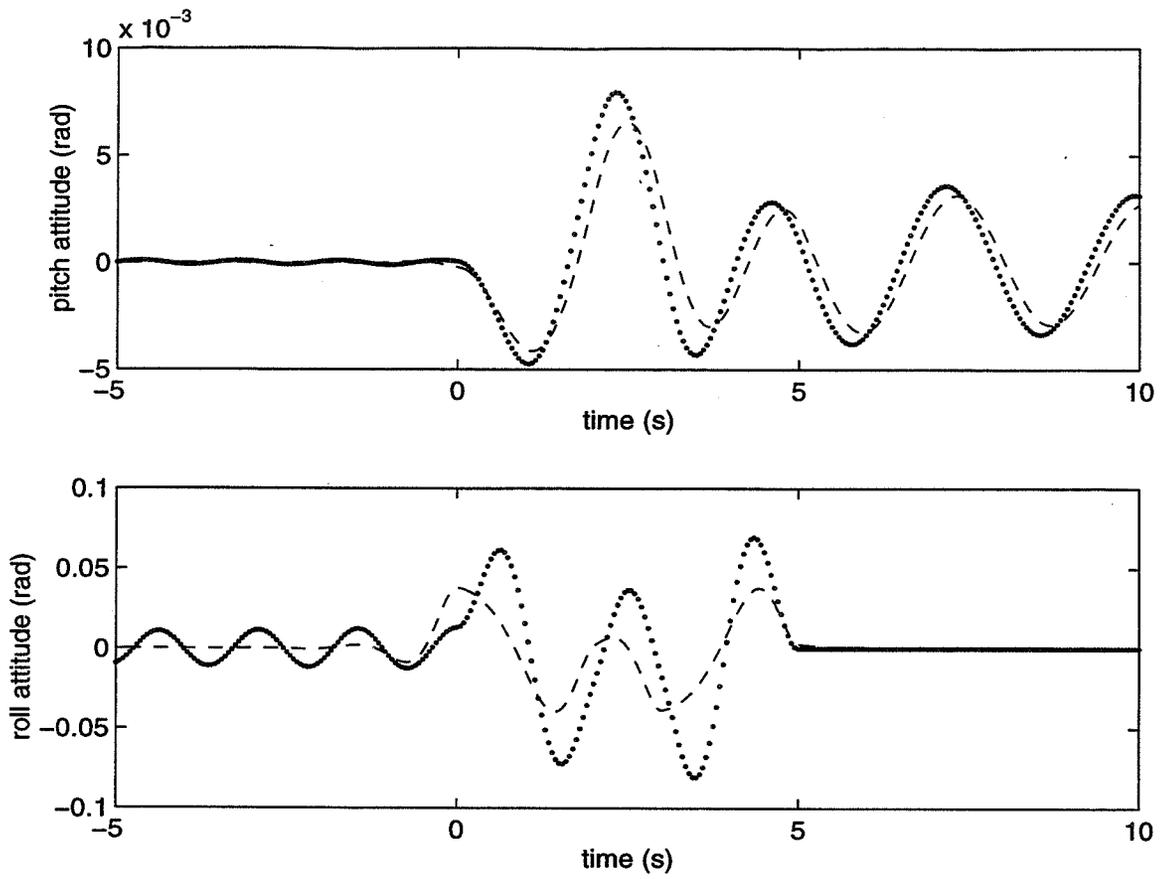


Figure 8. Internal Dynamics. Dotted line is without modification of internal dynamics and the dashed line is with modification.

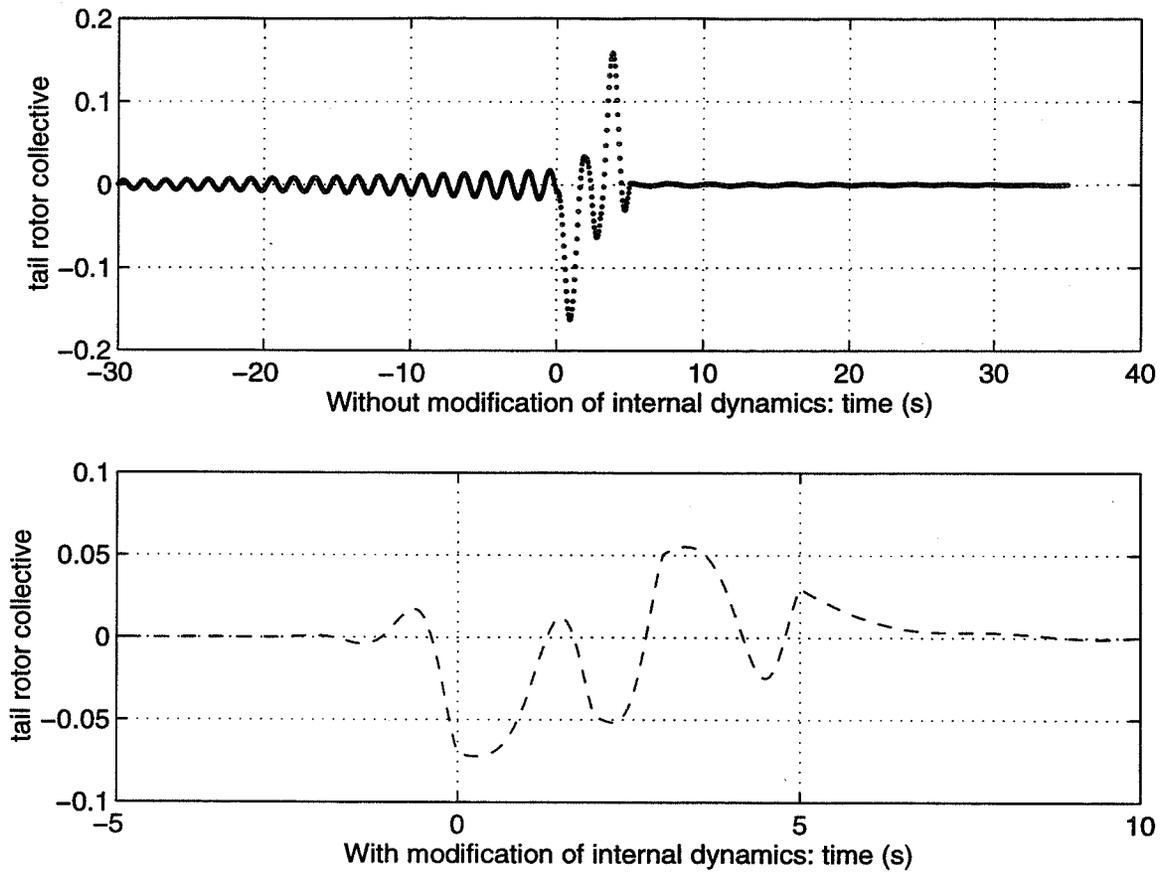


Figure 9. Comparison of Required Preactuation in the Feedforward.

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Exact-Output Tracking Theory for Systems with Parameter Jumps *

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Abstract - In this paper we consider the exact output tracking problem for systems with parameter jumps. Necessary and sufficient conditions are derived for the elimination of switching-introduced output transient. Previous works have studied this problem by developing a regulator that maintains exact tracking through parameter jumps (switches). Such techniques are, however, only applicable to minimum-phase systems. In contrast, our approach is applicable to nonminimum-phase systems and obtains bounded but possibly non-causal solutions. If the reference trajectories are generated by an exosystem, then we develop an exact-tracking controller in a feedback form. As in standard regulator theory, we obtain a linear map from the states of the exosystem to the desired system state which is defined via a matrix differential equation. The constant solution of this differential equation provides asymptotic tracking, and coincides with the feedback law used in standard regulator theory. The obtained results are applied to a simple flexible manipulator with jumps in the pay-load mass.

1. INTRODUCTION

We study the exact-output tracking of systems, which are described by

$$\begin{cases} \dot{x}(t) = A[k(t)]x(t) + B[k(t)]u(t) \\ y(t) = C[k(t)]x(t) \end{cases} \quad (1)$$

where $x \in \mathbb{R}^n$, with same number of inputs as outputs $u(t), y(t) \in \mathbb{R}^p$. The system matrices $A(k), B(k), C(k)$ are constant over time intervals I_k , where k belongs to a finite index set $\mathcal{K} \triangleq [0, \dots, N]$, and the parameter change (switch) at times $t = t_1, t_2, \dots, t_N$, (See Figure 1). Here, the switching time are known, in contrast to systems where the switches may be signal driven.

For constant linear systems, the asymptotic output-tracking problems for constant linear systems has received much attention in the past. In particular, the regulator theory (*Francis (1977); Basile and Marro (1992); Wonham (1985)*) provides a general framework in which the asymptotic output tracking can be solved when the reference trajectory is generated through a linear exosystem. In the presence of switches in the system, one technique for achieving output regulation is to switch the regulator. Note that regulation can be recovered between two consecutive switches (due to asymptotic properties) – especially if the switching occurs far apart in time. However, this technique also tends to induce transients in the output during the switches.

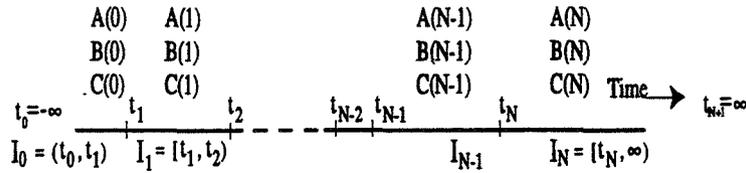


Figure 1: *The Switching Times*

In order to eliminate these *switching-caused* transients, a regulation scheme that maintains exact trajectory tracking across system switches must be used. This fairly new problem has been studied in (*Marro and Piazzi (1993)*), for minimum-phase systems. In this work, a feedforward action is used in conjunction with the feedback defined by the regulator in order to cancel the output transients across the switches.

In the present paper we propose an alternative approach for exact output-tracking of switched-systems, which is also applicable to nonminimum-phase systems. In the nonminimum-phase case, a bounded non-causal solution is obtained (*Devasia et al. (1996)*) that requires the preknowledge of the reference trajectory and of all the switching times. Such exact tracking schemes based on noncausal schemes is useful in problems like aircraft guidance (*Meyer et al. (1995)* and *Hunt et al. (1996)*).

We present necessary and sufficient conditions for the solvability of the inversion problem for linear systems with switches; the inverse is used to track the desired output. We consider two kinds of desired output trajectories: (a) a single pre-specified trajectory or (b) belonging to a class of outputs generated by a given linear exosystem, that could undergo parameter changes as well. In this latter case, we obtain the solution in a time-varying feedback form, where the feedback matrix satisfies a matrix ordinary differential equation. The equilibrium solution of this differential equation solves the asymptotic output tracking problem, and coincides with the feedback matrix resulting from the standard regulator. This establishes an interesting connection between our approach and the traditional regulator theory.

The paper is organized as follows: in Section 2 the exact tracking of a single prescribed output trajectory is considered, and necessary and sufficient conditions are presented. A geometric version of the obtained conditions is

also provided. In Section 3, the case of reference trajectory obtained through a linear exosystem will be treated. The conditions of the previous section when rearranged establish a close relationship with the traditional theory of output regulation. Section 4 focuses on the additional problem of stability of the closed loop system. Finally, section 5 presents the application of the developed theory to a simple nonminimum-phase switched system, given by a flexible beam subjected to step variation of the pay-load mass. Conclusions end the paper.

2. TRACKING A PRESCRIBED OUTPUT TRAJECTORY

Below we formulate the exact tracking problem for a prescribed output trajectory, and establish necessary and sufficient conditions for its solvability. Geometric interpretations of these conditions are also provided.

The Inversion Problem

Given a desired output trajectory y_d , find a pair of state and input trajectories x_d, u_d such that

1. x_d, u_d satisfy the system equation (1):

$$\dot{x}_d(t) = A[k(t)]x_d(t) + B[k(t)]u_d(t); \quad \forall t \in (-\infty, \infty), \quad (2)$$

2. exact output tracking is achieved (even across switches):

$$y_d(t) = C[k(t)]x_d(t); \quad \forall t \in (-\infty, \infty),$$

3. and the inputs and state are bounded:

$$\|x_d(\cdot)\|_\infty < \infty,$$

$$\|u_d(\cdot)\|_\infty < \infty.$$

Using the Inverse for Exact-Output Tracking

The existence of an inverse (u_d, x_d) implies that there are input-state trajectories that yield the desired output – exact output tracking is easily achieved by stabilizing the desired state trajectory. For example, use u_d as feedforward and use the error $x - x_d$ for feedback (see Figure 2). Stabilization is not the central issue in this paper, and any scheme for feedback design can

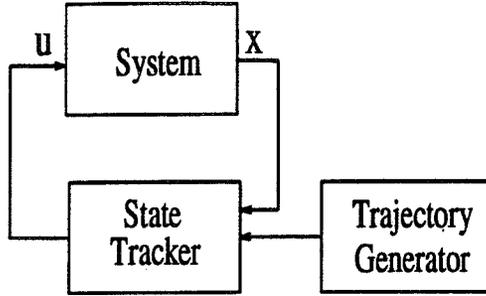


Figure 2: *The Control Scheme*

be used. For example, given $(A(k), B(k))$ controllable for all k , the system may be stabilized through pole placement with all the closed loop poles in the same locations for all k .

Note that typically, the initial conditions of the system are different from the initial conditions of the desired state trajectory leading to initial transient errors typical of all tracking controllers. However, once the desired level of tracking is achieved (due to exponential reduction in error) our technique will maintain tracking across parameter switches. In contrast, switching standard regulators when the system parameters change will cause transient errors at the switching instants – tracking will not be maintained across switches.

Exact-Tracking Maintaining Input

We will assume the following:

Assumption 1 *System $A(k), B(k), C(k)$ has well defined vector relative degree (Isidori (1989)) for each $k \in \mathcal{K}$.*

Then we can find a co-ordinate transformation \hat{Q}_k such that (Isidori (1989))

$$\begin{bmatrix} Y_k(t) \\ z_k(t) \end{bmatrix} = \hat{Q}_k x(t) = \begin{bmatrix} C_k^* \\ Z_k \end{bmatrix} x(t)$$

where

$$Y_k(t) = [y_1, \dot{y}_1, \dots, \frac{d^{(r_{k,1}-1)}}{dt^{(r_{k,1}-1)}} y_1, y_2, \dot{y}_2, \dots, \frac{d^{(r_{k,2}-1)}}{dt^{(r_{k,2}-1)}} y_2, \dots, y_p, \dot{y}_p, \dots, \frac{d^{(r_{k,p}-1)}}{dt^{(r_{k,p}-1)}} y_p]' ,$$

and $r_k = [r_{k,1}, r_{k,2}, \dots, r_{k,p}]$ is the systems vector relative degree for $t_k \leq t \leq t_{k+1}$ (where we assume $t_0 = -\infty$). Here, C_k^* maps the system states into

the outputs and its time derivatives and Z_k maps the states into the internal dynamics, z_k .

Note that a necessary condition for exact output tracking in the interval I_k is that the system state at time t_k is such that

$$Y_k(t_k) = Y_{k,d}(t_k)$$

In addition, to maintain exact tracking we need to ensure that

$$\dot{Y}_k(t) = \dot{Y}_{k,d}(t) \quad \forall t \in [t_k, t_{k+1})$$

Let

$$y_d^{(r_k)} = \left[\frac{d^{(r_{k,1})}}{dt^{(r_{k,1})}} y_{d,1}, \frac{d^{(r_{k,2})}}{dt^{(r_{k,2})}} y_{d,2}, \dots, \frac{d^{(r_{k,p})}}{dt^{(r_{k,p})}} y_{d,p} \right]',$$

then we can find the following unique control law (provided assumption 1 is satisfied) (*Isidori (1989)*)

$$u_d(t) = F_k x(t) + G_k y_d^{(r_k)}(t) \quad (3)$$

such that the time derivatives of the output is the same as that of the desired output trajectory y_d (this is also a necessary condition for exact output tracking). This exact-tracking control is completely determined by the state $x(t_k)$, and by the desired output along with its derivatives up to the order r_k .

Substituting control law (3) in (2) we obtain for $t \in I_k$:

$$\dot{x}(t) = A_y(k)x(t) + B_y(k)y_d^{(r_k)}(t) \quad (4)$$

where $A_y(k) = A(k) + B(k)F_k$, $B_y(k) = B(k)G_k$. In the transformed coordinates the system equations for $t \in I_k$ are of the form

$$\begin{aligned} \dot{Y}_k(t) &= \dot{Y}_{k,d}(t) \\ \dot{z}_k(t) &= A_z(k)z_k(t) + A_{z,y}(k)Y_k(t) + B_z(k)y_d^{(r_k)}(t) \end{aligned} \quad (5)$$

Our objective is to define under which conditions it is possible to define a feasible state trajectory $x_d(t)$ such that exact trajectory tracking is preserved through all the time intervals. There are two main hurdles. Firstly, the existence of at least a state trajectory which maintains exact output tracking has to be determined. This depends on *compatibility* of the desired output

with the given system. Secondly, the state trajectories have to be bounded. In systems with unstable internal-dynamics (nonminimum phase systems) generic solutions tend to be unbounded. In this case, we need to establish additional conditions for the existence of bounded solutions to the internal dynamics.

In this paper, we restrict ourselves to the case where (a) $Y_{k,d}$, the output along with its time derivatives, has a compact support $[T_i, T_f] \in (-\infty, \infty)$, (b) the switching occurs within this compact set, and (c) the internal-dynamics is hyperbolic. More formally

Assumption 2 *The desired output trajectory $y_d(\cdot)$ and its time derivatives are bounded and have compact support $S(y_d) = [T_i, T_f]$. The switching in the system parameters are at fixed times $t_k \in (T_i, T_f)$ for every $k \in [1, \dots, N]$.*

Assumption 3 *System (1) has hyperbolic internal dynamics, i.e. the eigenvalues of $A_z(k)$ have non-zero real parts (no centers) for $k = 0$ and $k = N$. This is equivalent to requiring that the original system (1) have no zeros which lie on the imaginary axis (Isidori (1989)) for $k = 0$ and $k = N$.*

The last assumption implies the existence of transformations Q_0, Q_N such that system state can be partitioned into

$$\begin{bmatrix} Y_k(t) \\ z_{sk}(t) \\ z_{uk}(t) \end{bmatrix} = Q_k x(t) = \begin{bmatrix} C_k^* \\ Z_{sk} \\ Z_{uk} \end{bmatrix} x(t) \quad (6)$$

where z_{sk} and z_{uk} are the coordinates for the stable and the unstable subspaces of the system's internal-dynamics.

Notations

Towards establishing conditions for the existence of solutions to the exact tracking problem for a prescribed output, we first study the dynamic evolution of the system for a given initial condition.

Given an initial condition in an interval I_k the system's evolution for $t_k \leq t \leq t_{k+1}$ is described by

$$x_d(t) = e^{A_y(k)(t-t_k)} x_d(t_k) + \int_{t_k}^t e^{A_y(k)(t-\tau)} B_y(k) y_d^{(r_k)}(\tau) d\tau.$$

In a more compact form

$$x_d(t) = \Phi_k(t, t_k)x_d(t_k) + h_k(t, t_k)$$

where

$$\Phi_k(t, t_k) = e^{A_y(k)(t-t_k)}$$

and

$$h_k(t, t_k) = \int_{t_k}^t e^{A_y(k)(t-\tau)} B_y(k) y_d^{(\tau_k)}(\tau) d\tau.$$

The above equations describe the flow in an interval where the system doesn't undergo switches. In order to obtain a representation of the system state in terms of an initial state that does not belong to the same interval, we define flow compositions as follows:

$$\Psi_{k,i}(t, t_i) = \Phi_k(t, t_k) \circ \Phi_{k-1}(t_k, t_{k-1}) \circ \dots \circ \Phi_i(t_{i+1}, t_i)$$

$$H_{k,i}(t, t_i) = h_k(t, t_k) + \sum_{j=i}^{k-1} \Psi_{k-1,j}(t_{k-1}, t_j) h_j(t_{j+1}, t_j)$$

where

$$\Psi_{i,i}(t, t_i) = \Phi_i(t, t_i)$$

and

$$H_{i,i}(t, t_i) = h_i(t, t_i)$$

The system evolution for an initial condition $x(T_i)$ can be rewritten as:

$$x(t) = \Psi_{k,0}(t, T_i)x(T_i) + H_{k,0}(t, T_i) \quad (7)$$

Necessary and Sufficient Conditions

We first formally state the result.

Lemma 1 *Under assumptions 1-3, the exact output tracking problem is solvable with bounded solution if and only if the system of equations:*

$$Y_{dk}(t_k) = C_k^* Q_k \Psi_{k-1,0}(t_k, T_i) Q_0^{-1} \begin{bmatrix} 0 \\ 0 \\ z_{u,0}(T_i) \end{bmatrix} + C_k^* Q_k H_{k-1,0}(t_k, T_i) \quad \forall k = 1, \dots, N \quad (8)$$

$$0 = Z_{uk}Q_N \left(\Psi_{N,0}(T_f, T_i)Q_0^{-1} \begin{bmatrix} 0 \\ 0 \\ z_{u,0}(T_i) \end{bmatrix} + H_{N,0}(T_f, T_i) \right) \quad (9)$$

admits solution in $z_{u,0}(T_i)$.

Proof. System trajectories outside $[T_i, T_f]$, the compact support of Y_d , are bounded if and only if z_{uN} , the unstable component of the internal-dynamics, is zero at the end of the motion T_f and similarly the stable component z_{s0} is zero before time T_i . Formally:

$$x(T_i) = Q_0^{-1} \begin{bmatrix} 0 \\ 0 \\ z_{u,0}(T_i) \end{bmatrix}$$

$$x(T_f) = Q_N^{-1} \begin{bmatrix} 0 \\ z_{s,N}(T_f) \\ 0 \end{bmatrix}$$

Substituting the previous expressions in (7) computed at $t = T_f$

$$x(T_f) = \Psi_{N,0}(T_f, T_i)x(T_i) + H_{N,0}(T_f, T_i)$$

gives (9). In addition, exact tracking in every interval I_k is possible if it is possible to find state trajectories that are continuous and such that $C_k^*x(t_k) = Y_{dk}(t_k)$. By using again (7) that gives the state at $t = t_k$ as a function of the initial state and the constraint on $x(T_i)$, (8) easily follows. ■

Equation (8) will be referred in the following as *compatibility conditions*, while equation (9) will be referred to as *stability condition*. The compatibility conditions ensure that Y_d does not jump across switches (else unbounded inputs will be required)! The stability condition ensures that the autonomous system dynamics for $t \rightarrow \pm\infty$ is bounded.

The algebraic conditions expressed by lemma 1 can also be interpreted in a geometric coordinate-free framework. To this end, let

$$\mathcal{L}_k = \{x : Y_k = Y_{d,k}(t_k)\} \quad k \in [0, \dots, N]$$

represents the set of the admissible system states at time t_k in order to achieve exact tracking in the time interval $t_k \leq t < t_{k+1}$. \mathcal{L}_k is in general

a linear variety in the state space, that reduces to a linear subspace (the system internal dynamics) for $k = 0$.

A necessary condition for achieving exact tracking when $t < T_i$ is $x_d(T_i) \in \mathcal{L}_0$. Further, to maintain a bounded solution for all $t < T_i$ it is necessary that the initial state belong to the unstable subspace of the system internal dynamics $x_d(T_i) \in \mathcal{L}_{u,0}$.

Note that every $x_d(T_i)$ determines a unique $x_d(t_1)$, given by

$$x_d(t_1) = \Phi_0(t_1, T_i)x_d(T_i) + h_0(t_1, T_i)$$

Hence, we can define the image of the subspace $\mathcal{L}_{u,0}$ as:

$$\Phi_0(t_1, t_0) \circ \mathcal{L}_{u,0} = \{x : x = \Phi_0(t_1, t_0)y + h_0(t_1, t_0); y \in \mathcal{L}_{u,0}\}$$

which represents the linear variety composed by the points reachable at time t_1 with the constraint of $y(t) = y_d(t)$ for all $t \in [t_0, t_1)$.

To maintain exact tracking in the next interval $t \in [t_1, t_2)$, it is necessary that $x_d(t_1) \in \mathcal{L}_1$. The compatibility condition at time $t = t_1$ states that

$$x_d(t_1) \in \mathcal{L}_1 \cap \Phi_0(t_1, T_i) \circ \mathcal{L}_{u,0}$$

which is possible if and only if the linear variety:

$$\mathcal{S}_1 = \mathcal{L}_1 \cap \Phi_0(t_1, T_i) \circ \mathcal{L}_{u,0}$$

is not empty, i.e. if and only if \mathcal{L}_1 intersects the image of $\mathcal{L}_{u,0}$ under the system flow. The same procedure can be repeated for the switching time $t = t_2$. Starting from \mathcal{S}_1 , we can flow forward in time. In order to achieve exact tracking in the interval $[t_2, t_3)$, the image of \mathcal{S}_1 must intersect \mathcal{L}_2 , i.e. the set

$$\mathcal{S}_2 = \mathcal{L}_2 \cap \Phi_1(t_2, t_1) \circ \mathcal{S}_1$$

must be not empty and more generally, the exact tracking in $t \in [T_i, t_{k+1})$ is possible if and only if the image of \mathcal{S}_{k-1} under the system flow $\Phi_{k-1}(t_k, t_{k-1})$ intersects \mathcal{L}_k , i.e. the set:

$$\mathcal{S}_k = \mathcal{L}_k \cap \Phi_{k-1}(t_k, t_{k-1}) \circ \mathcal{S}_{k-1} \quad (10)$$

is not empty for every $k = 1, \dots, N$. However, in order to obtain a bounded solution for $t > T_f$, the final state at time $t = T_f$ must belong to the stable subspace of the system internal dynamics $\mathcal{L}_{s,N}$. Let

$$\mathcal{S}_{T_f} \triangleq \mathcal{L}_{s,N} \cap \Phi_N(T_f, t_N) \circ \mathcal{S}_N.$$

Hence, we have proved an analogue of lemma 1 in geometric terms

Lemma 2 *The exact output tracking problem is solvable if and only if \mathcal{S}_{T_f} is non-empty, i.e.,*

$$\mathcal{S}_{T_f} \neq \emptyset. \quad (11)$$

Since the flow of a linear system is a homeomorphism, the dimension of a linear variety and that of its image are equal, and hence:

$$\dim(\tilde{\mathcal{S}}_i) \geq \dim(\mathcal{S}_j); \quad j \geq i$$

This means that at each iteration (10) the set of possible solutions could reduce at each K and that no solution is possible if it becomes the empty set for some k - i.e., it is empty for every $j \geq k$.

Switched systems with invariant internal-dynamics subspace

We present below a particular case in which the given conditions considerably simplify. This exemplifies the obtained results and will be illustrated with an example in section 5. Let

Assumption 4 *System (1) has constant relative degree $r = r_k$ for every k and matrix $C_k^* = C^*$ is constant for every k .*

It follows from the previous assumption that the coordinates outside the internal dynamics Y_k are the same for every k , and thus the internal dynamics subspace is the same for every k . Note that the stable and unstable subspaces may still be different, and may switch around, but are constrained to belong to the same subspace!

Since $Y_k = C^*x$, the continuity of x implies that the compatibility conditions are always satisfied. Formally.

Lemma 3 *If assumption 4 is satisfied, then the compatibility conditions are satisfied for every smooth enough (C^r) desired output trajectory $y_d(t)$.*

In addition, $\Phi_k(t_{k+1}, t_k) \circ \mathcal{S}_k \subset \mathcal{L}_{k+1}$ implies that

$$\mathcal{S}_{k+1} = \Phi_k(t_{k+1}, t_k) \circ \mathcal{S}_k$$

is nonempty since $0 \in \mathcal{S}_0$. Further $\dim(\mathcal{S}_n) = \dim(\mathcal{L}_{0,u})$.

The additional condition for boundedness of solutions for $t > T_f$ is met if and only if \mathcal{S}_N intersects $\mathcal{L}_{s,N}$. The linear variety \mathcal{S}_N can be expressed as

$$\mathcal{S}_N = \text{Im}(S_N) + v$$

while the stable subspace of the internal dynamics can be expressed as

$$\mathcal{L}_{s,N} = \text{Im}(L_{s,N}).$$

It immediately follows from the previous considerations:

Lemma 4 *If assumptions 1-4 hold, then the exact output tracking problem with bounded solution is solvable if*

$$\text{rank} \begin{bmatrix} S_N & L_{N,s} \end{bmatrix} = n_z \quad (12)$$

where n_z is the dimension of the system internal dynamics at $t = T_f$.

As a last remark to this section, note that if not only the internal dynamics subspace remains constant across the switchings as ensured by Assumption 4, but also its stable and unstable subspaces do, then condition (12) is always satisfied and the problem has a solution for every admissible $y_d(t)$. Moreover, this solution is unique for every given $y_d(t)$. This implies that the exact-tracking problem for a system without switches is always solvable.

3. y_d GIVEN THROUGH AN EXOSYSTEM

In this section we consider how the previous results can be specified when the reference trajectory is not completely general but it is generated through a known linear exosystem, given by:

$$\begin{cases} \dot{x}_e = A_e(k)x_e \\ y_d = C_e(k)x_e \end{cases} \quad (13)$$

First we solve the tracking problem when the initial state of the exosystem (at time T_i) is known in advance, hence the obtained result will be valid for the particular reference trajectory determined by the initial condition. Later, we will extend the approach to the case of unknown initial conditions. In

this case, we look for asymptotic tracking of the reference trajectories for arbitrary initial conditions of the exosystem.

We begin by studying the case where the state of the exosystem $x_e(T_i)$ is known. The system equation (4) becomes

$$\dot{x}_d(t) = A_y(k)x(t) + B_y(k)C_e^*(k)x_e(t), \quad (14)$$

with $y_d^{(r_k)}(t) \triangleq C_e^*(k)x_e(t)$ since all the time derivatives of the output can be written in terms of x_e by using equation 13.

The system evolution can then be rewritten as

$$x(t) = \Psi_{k,0}(t, T_i)x(T_i) + \hat{H}_{k,0}(t, T_i)x_e(T_i) \quad (15)$$

where

$$\begin{aligned} \hat{H}_{k,i}(t, t_i) &= \hat{h}_k(t, t_k) + \sum_{j=i}^{k-1} \Psi_{k-1,j}(t_{k-1}, t_j) \hat{h}_j(t_{j+1}, t_j), \\ \hat{h}_k(t, t_k) &= \int_{t_k}^t e^{A_y(k)(t-\tau)} B_y(k) C_e^*(k) \hat{\Psi}_{k,0}(\tau, T_i) d\tau. \end{aligned}$$

and $\hat{\Psi}_{k,0}(\tau, T_i)$ is the evolution of the exosystem (analogous to equation 7). A solution to the exact tracking problem exists if lemma 2 is satisfied. The compatibility condition is satisfied for all initial conditions $x_d(T_i) \in \mathcal{L}_0$ if $C_e^* = C^*$. The stability condition becomes

$$0 = s_1 z_{u,0}(T_i) + s_2 x_e(T_i). \quad (16)$$

where

$$\begin{aligned} s_1 &= Z_{uN} \Psi_{N,0}(T_f, T_i) Q_0^{-1} \begin{bmatrix} 0 \\ 0 \\ I z_{u,0}(T_i) \end{bmatrix} \\ s_2 &= Z_{uN} \hat{H}_{N,0}(T_f, T_i) \end{aligned}$$

In what is to follow, we will assume that the above equation has a unique solution (iff s_1 is invertible). This yields a one to one relationship between the plant's state and the exosystem as follows

$$\begin{aligned} x_d(T_i) &= Q_0^{-1} \begin{bmatrix} 0 \\ 0 \\ z_{u,T_i}(T_i) \end{bmatrix} \\ &= Q_0^{-1} \begin{bmatrix} 0 \\ 0 \\ -s_1^{-1} s_2 x_e(T_i) \end{bmatrix} \triangleq G(T_i) x_e(T_i) \end{aligned}$$

What is interesting is that we can also write the desired exact tracking state trajectory in terms of the exosystem state. Substituting the above expression in equation (15) we get

$$x_d(t) = G(t)x_e(t)$$

where

$$G(t) \triangleq \left[\Psi_{k,T_i}(t, T_i)G(T_i) + \hat{H}_{k,T_i}(t, T_i)C_e^* \right] \hat{\Psi}_{k,0}^{-1}(N, T_i)x_e(t) \quad (17)$$

It may be verified that $G(t)$ satisfies the differential equation

$$\dot{G}_k(t) = A_y(k)G_k(t) - G_k^T(t)A_e(k) + C_e^*.$$

In the case of no switching a constant solution always exists for the above Lyapunov equation provided the eigenvalues of the exosystem A_e are different from the zeros of the plant eigenvalues of A_y . The above equation also provides a control strategy when the exosystem states are not known. We estimate the state of the exosystem as \hat{x}_e and regulate the trajectory $\hat{x}_d = G(t)\hat{x}_e$. The stability of such a controller is studied in the next section.

4. STABILIZATION

If the state of the exosystem x_e is not known, then we could estimate it as \hat{x}_e with $\|x_e(t) - \hat{x}_e(t)\|_2 \leq K_e e^{\alpha_e t} \|x_e(0) - \hat{x}_e(0)\|_2$. We use $\hat{x}_d(t) = G(t)\hat{x}_e(t)$ as the estimated desired state trajectory, and stabilize this trajectory by using the control scheme shown in Figure 3. Note that the feedforward used (equation 3) is completely specified in terms of the exosystem's state-estimate as follows

$$\begin{aligned} u_d &= F_{k,1}x_d(t) + F_{k,2}y_d^{(r_k)}(t) \\ &= F_{k,1}G(t)\hat{x}_e(t) + F_{k,2}C_e^*\hat{x}_e(t) \\ &\triangleq F_k\hat{x}_e(t). \end{aligned}$$

The state equations are of the form

$$\dot{x} = A_k x + B_k (F_k \hat{x}_e + K(x - G(t)\hat{x}_e)) .$$

We require that the system in each interval is either stable or stabilizable. For simplicity, we assume that $A(k) + B(k)K$ is Hurwitz for all k - the

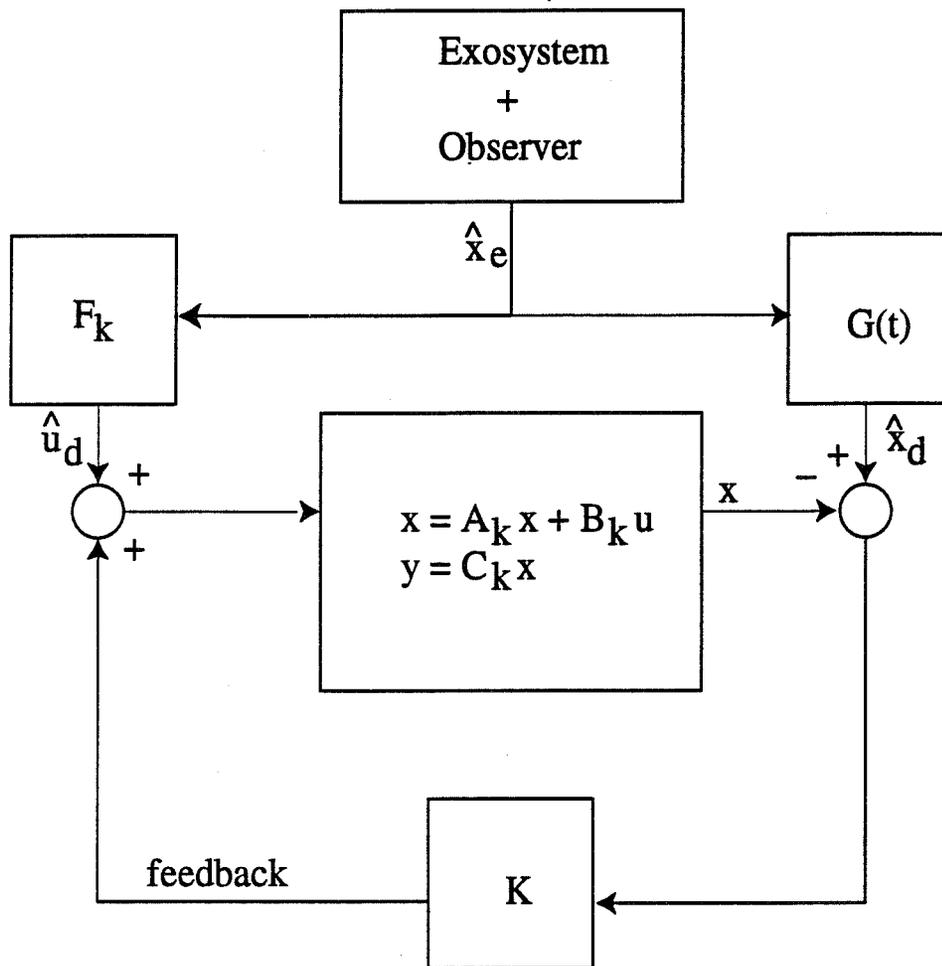


Figure 3: *Trajectory Tracking with Exosystem*

arguments remain valid if the system is stabilized through any other feedback control scheme.

The desired trajectory satisfies

$$\dot{x}_d = A_k x_d + B_k F_k x_e.$$

Let $e := x - x_d$. Then the difference of the last two equations yields

$$\dot{e} = (A_k + B_k K)e + (B_k F_k + B_k K G(t))(\hat{x}_e - x_e)$$

The exponential stability of the error dynamics system follows from the following lemma

Lemma 5 *Given the system $\dot{e} = Ae + v(t)$ where $K_1 e^{\alpha_1 t} < \|e^{-At}\|_2 < K_2 e^{\alpha_2 t}$ and $\|v(t)\|_2 < K_3 e^{-\alpha_3 t}$, with K_1, K_2, K_3 positive, then $e = 0$ is an exponentially stable equilibrium point provided $\alpha_3 > \alpha_2 > 0$*

Proof: Using the variation of constants formula

$$\begin{aligned} \|e^{-At}e(t)\|_2 &\leq \|e(0) + \int_0^t e^{-A\tau}v(\tau)d\tau\|_2 \\ &\leq \|e(0)\|_2 + \|\int_0^t e^{-A\tau}v(\tau)d\tau\|_2 \\ &\leq \|e(0)\|_2 + \int_0^t \|e^{-A\tau}v(\tau)\|_2 d\tau \\ &\leq \|e(0)\|_2 + K_2 K_3 \int_0^t e^{\alpha_2 - \alpha_3} d\tau \\ &\leq \|e(0)\|_2 + K_2 K_3 \frac{1}{\alpha_3 - \alpha_2} \end{aligned}$$

provided $\alpha_3 > \alpha_2$. Hence

$$K_1 \|e^{\alpha_1 t}e(t)\|_2 \leq \|e^{-At}e(t)\|_2 \leq \|e(0)\|_2 + K_2 K_3 \frac{1}{\alpha_3 - \alpha_2}$$

the rhs being a constant. Therefore, for all $\epsilon > 0$ there exists a positive constant K such that

$$\|e(t)\|_2 < K e^{-(\alpha_1 - \epsilon)t}$$

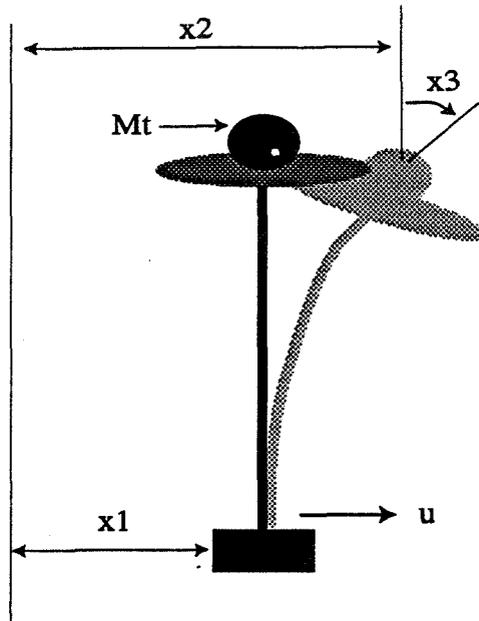


Figure 4: *Example*

5. EXAMPLE

Consider the flexible structure, cantilevered at the base and free at the top, shown in figure 4. It is modeled (with Finite Element Method) with a single flexural element. The degrees of freedom are the translational motion at the base (x_1), and the top (x_2), and the rotation at the top, x_3 . Input is a translational force at the base and the system output is x_2 . The structure is loaded with a mass m_t , which is changed at several instances. The flexural element has the following properties: mass 420; length 1; elastic modulus 1; and cross sectional area moment of inertia 1. The objective is to maintain the top of the structure along a prescribed trajectory so as to facilitate the transfer of the load. The equations of motion can be described by

$$M\ddot{x} + Sx = \hat{B}u$$

where

$$M = \begin{bmatrix} 156 & 54 & -13 \\ 54 & 156 + m_t & -22 \\ -13 & -22 & 4 \end{bmatrix} \quad S = \begin{bmatrix} 12 & -12 & 6 \\ -12 & 12 & -6 \\ 6 & -6 & 4 \end{bmatrix}$$

$x = [x_1 \ x_2 \ x_3]'$, and $\hat{B} = [1 \ 0 \ 0]'$.

In the standard form $x = [x', \dot{x}]'$ (abuse of notation) we get the dynamics as

$$\begin{aligned}\dot{x} &= A_k x + B_k u \\ y_k &= C_k x\end{aligned}$$

where

$$A_k = \begin{bmatrix} 0 & I \\ -M^{-1}S & 0 \end{bmatrix}; \quad B_k = \begin{bmatrix} 0 \\ M^{-1}\hat{B} \end{bmatrix}; \quad C_k = [0 \ 1 \ 0 \ 0 \ 0 \ 0];$$

The desired trajectory is generated by an exosystem of the form $\dot{x}_e = A_e x_e$, where

$$A_e = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

and the desired output is $y_d = [0 \ 0 \ 0 \ 1]x_e \triangleq C_e x_e$. We also switch the exosystem to $A_e = 0^{4 \times 4}$ at the initial and final times $T_i = 0$ and $T_f = 2 * \pi$. The first two states of the exosystem form an oscillator and the second state is then integrated twice to obtain the desired output. Note that (A_e, C_e) is observable. Hence the exosystem states can be estimated. In our simulations we ensure that the output trajectories have a compact support $[0, 2\pi]$ by choosing initial conditions of the exosystem of the form $x_e(T_i) = [0; *; 0; 0]$.

We also switch the mass m_t on the structure (see figure 4) to take values $m_t = 0 \ \forall t \in [0, \pi/2]$, $m_t = 100 \ \forall t \in (\pi/2, 1.5\pi]$, and $m_t = 10 \ \forall t \in (1.5\pi, 2\pi]$, which denotes the jumps in the system. Note that C_k^* remains constant through the switches and hence the compatibility conditions are always satisfied. As illustrated in Section 3, the map $G(0) : x_e(T_i) \rightarrow x_d(T_i)$ is given as

$$G(0) = \begin{bmatrix} -4.6715 & -3.3239 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 6.9406 & 2.6672 & 0 & 0 \\ -0.5935 & -1.4710 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 2.6851 & -0.8211 & 0 & 0 \end{bmatrix}$$

As an example we simulate the forward dynamics with the initial condition for the exosystem as $[0 \ 1 \ 0 \ 0]'$. The corresponding initial system state for

exact output tracking is $x_d(T_i) = [-3.3239 \ 0 \ 2.6672 \ -1.471 \ 0 \ -.8211]'$. The simulation results are shown in Figure 5, where the exact tracking state trajectory is shown – this desired state trajectory yields the desired output with an error of 10^{-6} for a motion of 2 units. This error is believed to be due to the numerical integration schemes. Further the initial conditions are large and unrealistic. The initial conditions of the system are typically not the same as the initial conditions of the desired state trajectory - this results in initial transient errors. If the system is stabilized then these errors decay exponentially, even if the system dynamics has switches. This ability to maintain tracking is a major advantage of our approach. Further, pre-actuation techniques to achieve these initial conditions (with output-error maintained at zero) has been developed in (*Devasia et al. (1996)*) and we expect to integrate the two approaches in the future.

CONCLUSIONS

The problem of achieving exact output tracking for linear systems that present jumps in parameter's values has been analyzed. We established necessary and sufficient conditions for the existence of exact output-tracking bounded state trajectories. When the reference trajectory is generated through an exosystem, the feedforward action needed to maintain exact tracking can be written as a time-varying feedback. Further, this time-varying feedback is related to a map from the state of the exosystem to the desired system state. The map is linear and is shown to satisfy an ordinary differential equation. For the case of systems without switches the theory presented reduces to the standard regulator theory. We also showed that the desired trajectory can be stabilized and presented the simulation results for an example flexible structure with *switchingmass*.

Future work will attempt to remove the requirement of compact support for the output. There is also a need to address the tracking problem for systems whose internal-dynamics may not be hyperbolic.

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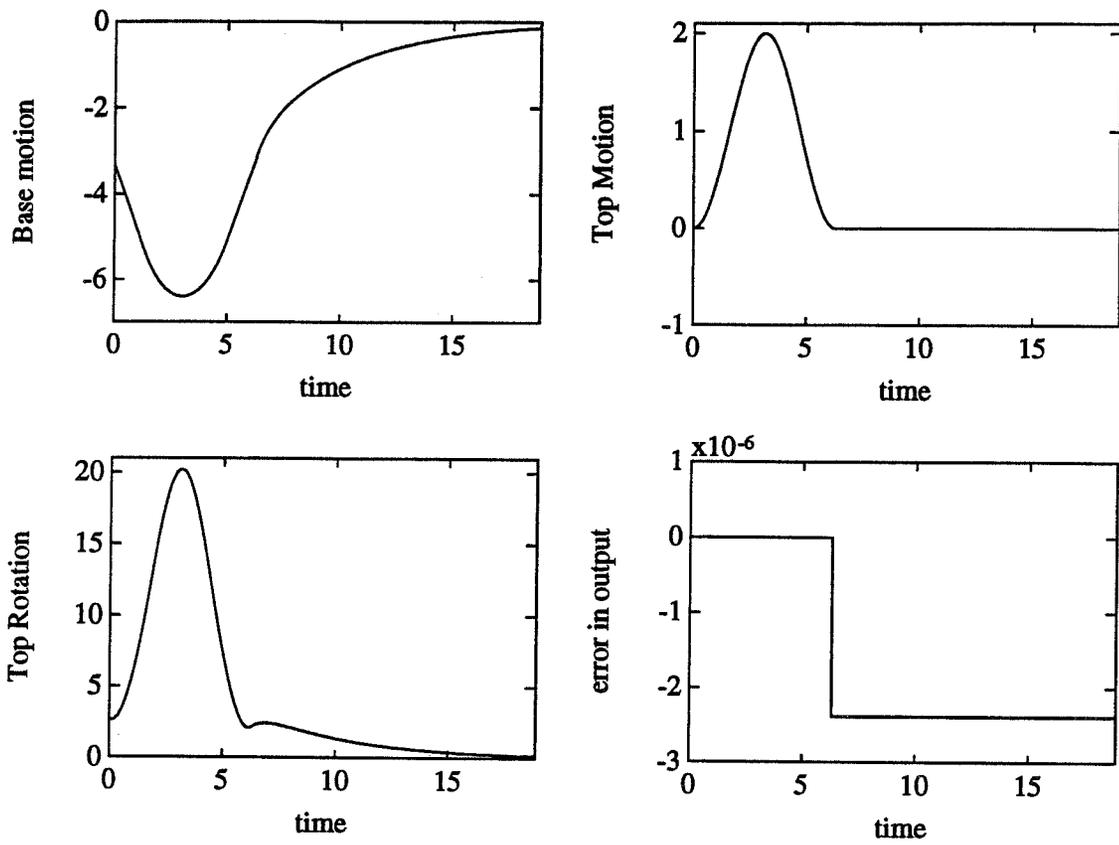


Figure 5: *Simulation results*

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Optimal Output Trajectory Redesign for Invertible Systems

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Optimal Output Trajectory Redesign for Invertible Systems

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I. Introduction

GIVEN a desired output trajectory, inversion-based techniques find input-state trajectories required to exactly track the output.^{1,2} These inversion-based techniques have been successfully applied to the endpoint tracking control of multijoint flexible manipulators in Ref. 3 and to aircraft control in Ref. 4. The specified output trajectory uniquely determines the required input and state trajectories that are found through inversion. These input-state trajectories exactly track the desired output; however, they might not meet acceptable performance requirements. For example, during slewing maneuvers of flexible structures, the structural deformations, which depend on the required state trajectories, may be unacceptably large. Further, the required inputs might cause actuator saturation during an exact tracking maneuver, for example, in the flight control of conventional takeoff and landing aircraft.⁵ In such situations, a compromise is desired between the tracking requirement and other goals such as reduction of internal vibrations and prevention of actuator saturation; the desired output trajectory needs to be redesigned.

Here, we pose the trajectory redesign problem as an optimization of a general quadratic cost function and solve it in the context of linear systems. The solution is obtained as an off-line prefilter of the desired output trajectory. An advantage of our technique is that the prefilter is independent of the particular trajectory. The prefilter can therefore be precomputed, which is a major advantage over other optimization approaches (see Ref. 6 for further references).

Previous works have addressed the issue of preshaping inputs to minimize residual and in-maneuver vibrations for flexible structures; see, for example, Refs. 6 and 7. Since the command preshaping is computed offline, in Ref. 8, the use of noncausal prefilters has been suggested—such noncausality is allowable since the command preshaping is computed off-line. Further, minimization of optimal quadratic cost functions has also been previously used to preshape command inputs for disturbance rejection in Ref. 9. All of these approaches are applicable when the inputs to the systems are known a priori. Typically, outputs (not inputs) are specified in tracking problems, and hence the input trajectories have to be computed. The inputs to the system are, however, difficult to determine for non-minimum phase systems like flexible structures. One approach to solve this problem is to 1) choose a tracking controller (the desired output trajectory is now an input to the closed-loop system) and 2) redesign this input to the closed-loop system. Thus, we effectively perform output redesign.⁶ These redesigns are, however, dependent on the choice of the tracking controllers.¹⁰ Thus, the controller optimization and trajectory redesign problems become coupled; this coupled optimization is still an open problem. In contrast, we decouple the trajectory redesign problem from the choice of feedback-based tracking controller. It is noted that our approach remains valid when a particular tracking controller is chosen. In addition, the formulation of our problem not only allows for the minimization of residual vibrations as in available techniques⁶ but also allows for the optimal reduction of vibrations during the maneuver, e.g., the altitude control of flexible spacecraft.⁹ We begin by formulating the optimal output trajectory redesign problem and then solve it in the context of general linear systems. This theory is then applied to an example flexible structure, and simulation results are provided.

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II. Problem Formulation

System Inversion for Exact Tracking

Consider a square system described by

$$\dot{x} = Ax + Bu; \quad y = Cx$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^p$, and $y \in \mathbb{R}^p$. The inversion approach² finds a bounded input-state trajectory that satisfies the preceding system equations and yields the exact desired output, i.e.,

$$\dot{x}_{\text{ref}} = Ax_{\text{ref}} + Bu_{\text{ff}}; \quad y_d = Cx_{\text{ref}}$$

The inverse input-state trajectories can be described in terms of Fourier transforms as^{1,11}

$$\begin{aligned} u_{\text{ff}}(j\omega) &= [C(j\omega I - A)^{-1}B]^{-1}y_d(j\omega) = G_y^{-1}(j\omega)y_d(j\omega) \\ x_{\text{ref}}(j\omega) &= [(j\omega I - A)^{-1}B]u_{\text{ff}}(j\omega) = G_x(j\omega)u_{\text{ff}}(j\omega) \end{aligned} \quad (1)$$

This Fourier-based inversion approach has been extended to nonlinear time-varying nonminimum phase systems in Ref. 2; however, we restrict our discussion to linear time-invariant systems.

Remark. We note two results. One, an inverse exists if the output and a certain number of its time derivatives are bounded. The number of time derivatives of the output that needs to be specified for an inverse to exist is well defined and depends on the relative degree of the system.^{2,12} Second, for linear hyperbolic systems, if the inverse exists, then it is unique.^{1,2}

Performance Criterion

Trajectory redesign seeks a compromise between the goal of tracking the desired trajectory and other goals such as reducing the magnitude of input and vibrations. We formulate this redesign problem as the minimization of a quadratic cost function of the type

$$\int_{-\infty}^{\infty} \{u(t)^T R u(t) + x(t)^T Q_x x(t) + [y(t) - y_d(t)]^T Q_y [y(t) - y_d(t)]\} dt$$

where R , Q_x , and Q_y represent the weight on control input, states, and the error in output tracking, respectively.

Using Parseval's theorem, we rewrite our optimization problem in frequency domain as the minimization of the cost function

$$\begin{aligned} J &= \int_{-\infty}^{\infty} \{u(j\omega)^* R u(j\omega) + x(j\omega)^* Q_x x(j\omega) \\ &+ [y(j\omega) - y_d(j\omega)]^* Q_y [y(j\omega) - y_d(j\omega)]\} d\omega \end{aligned} \quad (2)$$

where the superscript * denotes complex conjugate transpose.

Optimal Redesign of the Output

Our main result is given by the following lemma, which shows that the optimal output trajectory redesign can be described as a prefilter, which maps desired output trajectories y_d to the redesigned output trajectory y_{opt} . This prefilter G_f does not depend on the particular choice of desired trajectory and hence can be precomputed.

Lemma. The modified output trajectory y_{opt} is given by $y_{\text{opt}}(j\omega) = G_f(j\omega)y_d(j\omega)$, where

$$\begin{aligned} G_f(j\omega) &= 1 - G_y [R + G_x^* Q_x G_x + G_y^* Q_y G_y]^{-1} \\ &\times [R + G_x^* Q_x G_x] G_y^{-1} \end{aligned}$$

The modified input trajectory u_{opt} is given by $u_{\text{opt}}(j\omega) = u_{\text{ff}}(j\omega) + v_{\text{opt}}(j\omega)$, where $v_{\text{opt}}(j\omega) = G_v(j\omega)y_d(j\omega)$ and

$$\begin{aligned} G_v(j\omega) &= -(R + G_x^* Q_x G_x + G_y^* Q_y G_y)^{-1} \\ &\times (R + G_x^* Q_x G_x) G_y^{-1} \end{aligned} \quad (3)$$

Note that the dependence on $j\omega$ is not explicitly written for compactness.

Proof. Without loss of generality, we rewrite the input u as the sum of the feedforward input, $G_y^{-1}y_d$, found from inversion of the desired trajectory, and an arbitrary v :

$$u(j\omega) = u_{\text{ff}}(j\omega) + v(j\omega) = G_y^{-1}(j\omega)y_d(j\omega) + v(j\omega) \quad (4)$$

Substituting $x(j\omega) = G_x(j\omega)u(j\omega)$ and $y(j\omega) = G_y(j\omega)u(j\omega)$ along with the preceding Eq. (4) for u into the cost function given by Eq. (2), we obtain

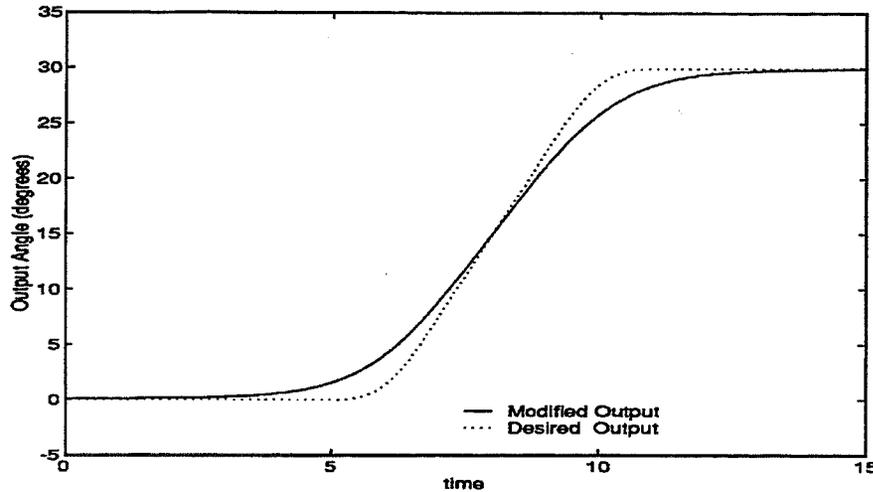


Fig. 1 Output redesign.

$$\begin{aligned}
 J = \int_{-\infty}^{\infty} & \{ [v + (R + G_x^* Q_x G_x + G_y^* Q_y G_y)^{-1} \\
 & \times (R + G_x^* Q_x G_x) G_y^{-1} y_d]^* * (R + G_x^* Q_x G_x + G_y^* Q_y G_y) \\
 & \times [v + (R + G_x^* Q_x G_x + G_y^* Q_y G_y)^{-1} \\
 & \times (R + G_x^* Q_x G_x) G_y^{-1} y_d] + (G_y^{-1} y_d)^* [(R + G_x^* Q_x G_x) \\
 & + (R + G_x^* Q_x G_x)^* * (R + G_x^* Q_x G_x + G_y^* Q_y G_y)^{-1} \\
 & \times (R + G_x^* Q_x G_x)] (G_y^{-1} y_d) \} dw
 \end{aligned}$$

Note that the cost function is quadratic in v . Therefore, the cost function is minimized by setting this quadratic term to zero, i.e., choosing $v(j\omega) = v_{\text{opt}}(j\omega) = G_v(j\omega)y_d(j\omega)$, where G_v is defined by Eq. (3) in the lemma. The choice of $v = v_{\text{opt}}$ defines the optimal input u_{opt} through Eq. (4) as

$$u_{\text{opt}}(j\omega) = [G_y^{-1}(j\omega) + G_v(j\omega)]y_d(j\omega) \quad (5)$$

The result follows from $y_{\text{opt}}(j\omega) = G_y(j\omega)u_{\text{opt}}(j\omega) = [1 + G_y(j\omega)G_v(j\omega)]y_d(j\omega)$. \square

III. Example

Consider a flexible structure consisting of two freely rotating disks connected by a thin shaft. A motor is attached between the connecting shaft and one of the disks. Input to the system is torque τ provided by a dc motor, and the outputs are the angular rotations of the two disks θ_1 and θ_2 . These angular rotations are measured using potentiometers. The transfer function of an experimental system, which includes the rigid-body mode and one flexible mode, was obtained using a HP3562A Dynamic Signal Analyzer as

$$\begin{aligned}
 \frac{\theta_1}{\tau} &= \frac{1.8139s^2 + 0.3077s + 6.1041}{s^4 + 0.2765s^3 + 6.1041s^2} \\
 \frac{\theta_2}{\tau} &= \frac{0.27s^2 - 0.1187s + 6.1041}{s^4 + 0.2765s^3 + 6.1041s^2}
 \end{aligned} \quad (6)$$

With the state vector x chosen as $x = [\theta_1 \ \theta_2 \ \dot{\theta}_1 \ \dot{\theta}_2]^T$, the system equations can be represented in state-space form as $\dot{x} = Ax + Bu$, i.e.,

$$\begin{aligned}
 \frac{d}{dt} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} &= \begin{bmatrix} 0 & 1 & 0 & 0 \\ -3.1555 & -0.1640 & 3.1555 & 0.3845 \\ 0 & 0 & 0 & 1 \\ 2.8956 & -0.0899 & -2.8956 & -0.1124 \end{bmatrix} \\
 &\times \begin{bmatrix} \theta_1 \\ \theta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} + \begin{bmatrix} 0 \\ 1.8139 \\ 0 \\ 0.27 \end{bmatrix} \tau
 \end{aligned}$$

with $y = \theta_2 = [0 \ 1 \ 0 \ 0]x$. The control objective is to track the angular rotation θ_2 of the disk that is farthest away from the motor (see Fig. 1 for the desired output trajectory).

The relative degree of a single-input/single-output linear system is the number of zeros at infinity.¹² For our system, with the torque as input and θ_2 as output, the transfer function has four poles and two finite zeros [see Eq. (6)]. Thus, the number of zeros at infinity are two, and hence the relative degree is two. This implies that the second derivative of the desired output, i.e., the desired angular acceleration profile of the output, uniquely determines the required input-state trajectory and the resulting structural vibration, $\theta_1 - \theta_2$.² If the internal vibrations are to be reduced, then we have to relax the exact tracking requirement. Similarly, to reduce the required input amplitudes we have to compromise exact tracking. This tradeoff can be represented as the minimization of a general quadratic cost function (Sec. II) of the form

$$\begin{aligned}
 \int_{-\infty}^{\infty} & \{ u(t)^T R u(t) + x(t)^T Q_x x(t) \\
 & + [y(t) - y_d(t)]^T Q_y [y(t) - y_d(t)] \} dt
 \end{aligned}$$

where $R = r$, $Q_y = q_y$, and

$$Q_x = q_x \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The scalars r , q_x , and q_y represent the relative weight on the reduction of inputs, structural vibrations, and tracking errors, respectively. To reduce the vibrations and control inputs, we choose $r = 1$, $q_x = 5000$, and $q_y = 1$ in our simulations. Figure 1 shows the modification for a desired trajectory—about 10% of the final slew angle. The maximum magnitude of the required input, however, is reduced by 60%, and the corresponding structural vibration, $\theta_1 - \theta_2$, is reduced by 20% (compared with results from exact tracking of the initial desired trajectory).

IV. Conclusion

We formulated and solved the trajectory redesign problem in the context of linear invertible systems, including nonminimum phase systems. Thus, we provide a systematic approach to an optimal tradeoff between tracking desired trajectory and other goals such as vibration reduction and reduction of required inputs. The approach was applied to an example flexible structure, and simulation results were presented. Future work will address trajectory redesign for nonlinear systems.

Acknowledgment

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Experimental and Theoretical Results in Output-Trajectory Redesign for Flexible Structures *

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Abstract

In this paper we study the optimal redesign of output trajectory for linear invertible systems. This is particularly important for tracking control of flexible structures because the input-state trajectories that achieve the required output may cause excessive vibrations in the structure. A trade-off is then required between tracking and vibrations reduction. We pose and solve this problem as the minimization of a quadratic cost function. The theory is developed and applied to the output tracking of a flexible structure and experimental results are presented.

1 Introduction

Large space structures, like manipulators used to assemble the space station, are lightweight, and hence flexible. The structural flexibility results in elastic vibrations. These vibrations are caused not only by exogenous perturbations but also arise during maneuvers like slewing. Hence the output tracking control for flexible structures is a formidable task. Recent works have solved the output tracking problem, for example, given a desired output trajectory, inversion-based techniques find

input-state trajectories that exactly track the output [1, 2, 3, 4]. These inversion-based techniques have been successfully applied to the control of multi-joint flexible manipulators in [5, 6], and to aircraft control in [7, 8, 9]. Note that the specified output trajectory uniquely determines the required input and state trajectories. Therefore, although these input-state trajectories exactly track the desired output, they might not meet performance requirements in flexible structures. For example, during slewing maneuvers of a flexible manipulator, the structural deformations - determined by the inverse state trajectories - may be unacceptably large. In such situations, a compromise is desired between the tracking requirement and the other goals like the reduction of internal vibrations and prevention of actuator saturation - the output trajectory needs to be redesigned.

Here, we pose the trajectory redesign problem as an optimization of a general quadratic cost function, and solve it in the context of linear systems. The solution is obtained as an off-line prefilter of the desired output trajectory. Thus the redesigned output trajectory can be obtained through a simple convolution similar to the convolutions prevalent in the command shaping approaches, see for example [10, 11]. An advantage of our technique is that the pre-filter is independent of the partic-

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ular trajectory. The pre-filter can therefore be pre-computed which is a major advantage over other optimization approaches (see [11] for references).

Previous works have addressed the issue of pre-shaping inputs, rather than desired outputs, to minimize residual and in-maneuver vibrations for flexible structures – see for example [11, 12, 13, 14, 15, 16]. Note that in these problems, the command preshaping is computed off-line, and hence noncausal pre-filters can be used [10]. Further, minimization of optimal quadratic cost functions have also been previously used to preshape command inputs for disturbance rejection in [17]. A common problem with all these approaches is that they are applicable when the inputs to the systems are known *a priori*. In tracking problems, however, outputs are usually specified and not the inputs: input trajectories have to be computed from the desired outputs. For nonminimum phase systems (flexible structures with non-collocated inputs and outputs) the inputs to the system are difficult to determine. One approach to solve this problem is to: (1) choose a tracking controller – the desired output trajectory is now an input to the closed loop system; and (2) redesign this *input* to the closed loop system. Thus, effectively, we perform output redesign [11]. These redesigns are, however, dependent on the choice of the tracking controllers [18]. Thus the controller optimization and trajectory redesign problems become coupled - this coupled optimization is still an open problem. In contrast, our optimal output trajectory redesign is independent of the particular choice of tracking controller. We can, therefore, decouple the trajectory redesign problem from the tracking-controller design. Note that if a particular closed loop controller is chosen, our approach is still valid. The formulation of our problem not only allows for the minimization of residual vibrations as in available techniques [11], but, additionally, allows for the optimal reduction of vibrations during the maneuver, which is required in maneuvers like the altitude control of flexible spacecraft [17].

We begin by formulating the optimal output trajectory redesign problem, and then solve it in the context of general linear systems. This theory is then applied to an example flexible structure and experimental results are provided.

2 Problem Formulation

System Inversion for Exact Tracking

Consider a square system described by

$$\begin{aligned}\dot{x} &= Ax + Bu \\ y &= Cx\end{aligned}$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^p$ and $y \in \mathbb{R}^p$. The inversion approach [4] finds a bounded input-state trajectory that satisfies the above system equations, and yields the exact desired output, i.e.

$$\begin{aligned}\dot{x}_{ref} &= Ax_{ref} + Bu_{ff} \\ y_d &= Cx_{ref}.\end{aligned}$$

The inverse input-state trajectories can be described in terms of Fourier transforms as [1, 2]

$$\begin{aligned}u_{ff}(j\omega) &= [C(j\omega I - A)^{-1}B]^{-1}y_d(j\omega) \\ &:= G_y^{-1}(j\omega)y_d(j\omega) \\ x_{ref}(j\omega) &= [(j\omega I - A)^{-1}B]u_{ff}(j\omega) \\ &:= G_x(j\omega)u_{ff}(j\omega).\end{aligned}\tag{1}$$

This Fourier based inversion approach has been extended to nonlinear time-varying nonminimum phase systems in [4], however, we restrict our discussion to linear time-invariant systems.

Remark I We note two results. One, an inverse exists if the output and a certain number of its time-derivatives are bounded. The number of time derivatives of the output that needs to be specified for an inverse to exist is well-defined and depends on the relative degree of the system [19, 4]). Second, for linear systems, if the inverse exists then it is unique [1, 2, 3, 4].

The Performance Criterion

Trajectory redesign seeks a compromise between the goal of tracking the desired trajectory and other goals like reducing the magnitude of input and vibrations. We formulate this redesign problem as the minimization of a quadratic cost function of the type

$$\int_{-\infty}^{\infty} \left\{ u(t)^T R u(t) + x(t)^T Q_x x(t) + [y(t) - y_d(t)]^T Q_y [y(t) - y_d(t)] \right\} dt \quad (2)$$

where R, Q_x and Q_y represents the weight on control input, states, and the error in output tracking respectively.

Using Parseval's theorem we rewrite our optimization problem in frequency domain as the minimization of the cost function

$$J := \int_{-\infty}^{\infty} \left\{ u(j\omega)^* R u(j\omega) + x(j\omega)^* Q_x x(j\omega) + [y(j\omega) - y_d(j\omega)]^* Q_y [y(j\omega) - y_d(j\omega)] \right\} d\omega$$

where the superscript $*$ denotes complex conjugate transpose.

Optimal Redesign of the Output

Our main result is given by the following lemma, which shows that the optimal output-trajectory redesign can be described as a pre-filter, which maps desired output trajectories, y_d , to the redesigned output trajectory, y_{opt} . This pre-filter, G_f , doesn't depend on the particular choice of desired trajectory and hence can be pre-computed.

Lemma The modified output trajectory, y_{opt} , is given by

$$y_{opt}(j\omega) = G_f(j\omega) y_d(j\omega)$$

where

$$G_f(j\omega) = 1 - G_y [R + G_x^* Q_x G_x + G_y^* Q_y G_y]^{-1} [R + G_x^* Q_x G_x] G_y^{-1}.$$

Proof: See [20] □

Remark II We point out two extreme cases. First, if the weight on the tracking error is zero, $Q_y = 0$, but R is positive definite then we obtain $v = -(G_y^{-1} y_d) = -u_{ff}$. This implies that the input $u_{opt} = u_{ff} + v = 0$, i.e., the best strategy is not to track the desired trajectory at all. It is more optimal to remain at the equilibrium point where the cost is zero. Second, if the weight on the inputs and states are zero, i.e., $R = 0$ and $Q_x = 0$ but with Q_y positive definite then $y_{opt} = y_d$. This implies that exact tracking is optimal, and the cost is again zero.

3 Example

Consider an experimental flexible structure which consists of two discs connected by a thin shaft as shown in figure 1. These two discs can rotate freely.

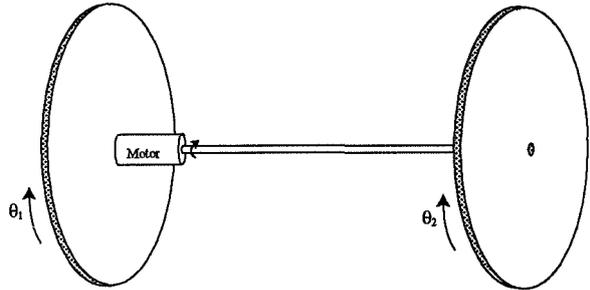


Figure 1 Schematic Experimental Setup

The transfer function of the system, which includes the rigid body mode and one flexible mode, was obtained experimentally using a HP3562A Dynamic Signal Analyzer. Input to the system is torque, τ , provided by a DC motor and the outputs are the angular rotations of the two discs θ_1, θ_2 . These angular rotations are measured using potentiometers, and the transfer functions are obtained as

$$\begin{aligned} \frac{\theta_1}{\tau} &= \frac{1.0684S^2 + 0.1812S + 3.5953}{S^4 + .2765S^3 + 6.1041S^2} \\ \frac{\theta_2}{\tau} &= \frac{.1590S^2 - 0.0699S + 3.5953}{S^4 + .2765S^3 + 6.1041S^2} \quad (3) \end{aligned}$$

With the state vector x chosen as

$$x := \begin{bmatrix} \theta_1 \\ \theta_2 \\ \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix}$$

the system equations can be represented in state-space form as

$$\dot{x} := Ax + Bu$$

$$y := \theta_2 = [0 \ 1 \ 0 \ 0]x$$

where

$$A := \begin{bmatrix} 0 & 1 & 0 & 0 \\ -3.2 & -0.16 & 3.2 & 0.38 \\ 0 & 0 & 0 & 1 \\ 2.9 & -0.09 & -2.9 & -0.11 \end{bmatrix},$$

$$B := \begin{bmatrix} 0 \\ 1.81 \\ 0 \\ 0.27 \end{bmatrix}.$$

The control objective is to track the angular rotation, θ_2 of the disc, that is farthest away from the motor (see figure 1). The desired output trajectory and its time-derivatives as prescribed as shown in figure 2.

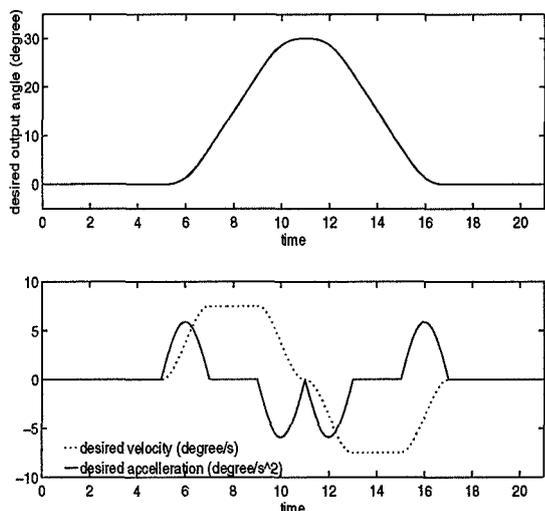


Figure 2 The Desired Output

The relative degree of a single-input single-output linear system is the number of zeros at infinity [19]. For our system, with the torque

as input and θ_2 as output, the transfer function has four poles and two finite zeros (see equation(3)). Thus the number of zeros at infinity are two and hence the relative degree is two. This implies that the second derivative of the desired output, i.e. the desired angular acceleration profile of the output, uniquely determines the required input-state trajectory, and the resulting structural vibration, $\theta_1 - \theta_2$ [4]. If the internal vibrations are to be reduced, then we have to relax the exact tracking requirement. Similarly to reduce the required input amplitudes we have to compromise exact tracking. This trade-off can be represented as the minimization of a a general quadratic cost function (section 2) of the form

$$\int_{-\infty}^{\infty} u(t)^T R u(t) + x(t)^T Q_x x(t) + (y(t) - y_d(t))^T Q_y (y(t) - y_d(t)) dt$$

where $R = r$, $Q_y = q_y$, and

$$Q_x = q_x \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

The scalars r, q_x, q_y represent the relative weight on the reduction of inputs, structural vibrations and tracking errors respectively. In order to reduce the vibrations and control inputs, we choose $r = 1, q_x = 5000$, and $q_y = 1$ in our simulations. Figure 3 shows the modification of the desired trajectory - about 10% of the final slew angle.

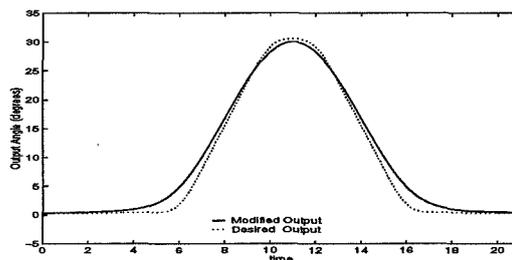


Figure 3 Simulation: Re-Designed Output

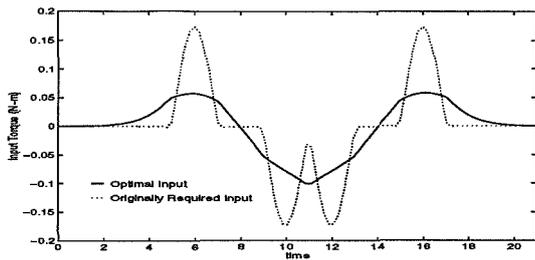


Figure 4 Optimal Input

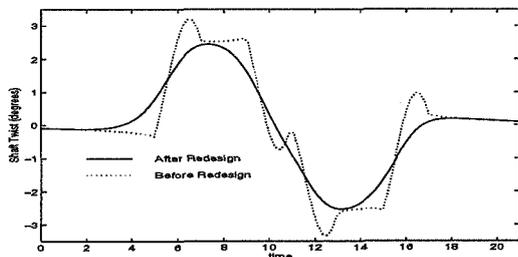


Figure 5 Simulation: Twisting of the Flexible Shaft

The maximum magnitude of the required input, however, is reduced by 60% and the structural vibrations, $\theta_1 - \theta_2$, is reduced by 20% as shown in figures 4 and 5. The input-state trajectories found through inversion as described in equation 1 : two simulations are performed, first with the original desired trajectory, y_d and second with the modified output trajectory, y_{opt} . These state trajectories are stabilized through feedback (see control scheme in figure 6), and preliminary experimental results are presented in figures 7 and 8.

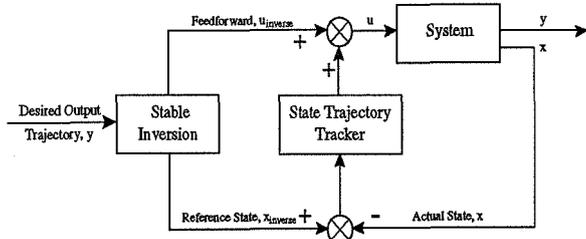


Figure 6 The Control Scheme

With the reference feedforward inputs as the original inversion input u_{ff} and the modified

(reduced) optimal input u_{opt} (figure 4), the experimental results verify that the small modification of the output trajectory (figure 7) reduces the maximum internal vibrations (50%, figure 8). Further reduction in the vibrations are possible if the tracking requirement (Q_y) is relaxed. Also, it is possible to stabilize the system first through the feedback loop and then apply the trajectory redesign scheme to the closed loop system - but the redesign for our control scheme will not change since the input state trajectories always satisfy the state equations and hence in the redesign the stabilizing feedback is zero. For example, (u_{ff}, x_{ref}) satisfies the state equations and thus the stabilizing feedback is zero if $x = x_{ref}$ and does not affect the output redesign.

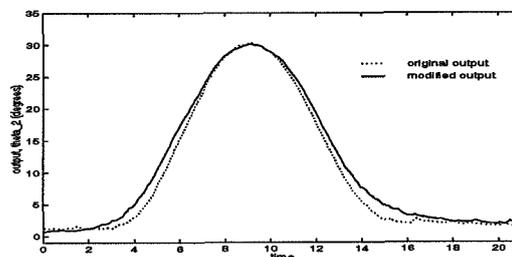


Figure 7 Experimental Results: The Tracking

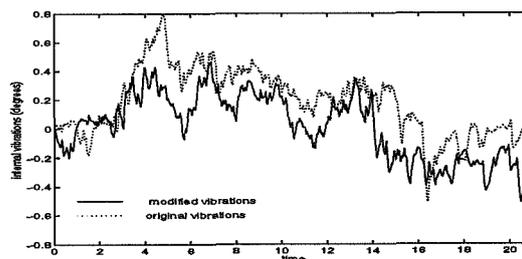


Figure 8 Experimental Results: The Internal Vibrations

4 Conclusion

We formulated and solved the trajectory redesign problem in the context of linear invertible systems - including nonminimum phase

systems. Thus we provide a systematic approach to an optimal tradeoff between tracking desired trajectory and other goals like vibration reduction and reduction of required inputs. The approach was applied to an example flexible structure and experimental results were presented. Future work will address trajectory redesign for nonlinear systems.

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