Manual Flight Control with Saturating Actuators

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The objectives of this article are to concisely state the tracking control problem with actuator saturation, briefly review the current literature, and formulate the problem in a manual (flight) control context. The complexity of tracking control with saturation is demonstrated via a "simple" example. A new approach to the manual flight control problem with both rate and amplitude actuator constraints, referred to as *Linear Quadratic Tracking* (LQT), is outlined. This approach is specifically directed toward the dynamic tracking control problem subject to both displacement and rate actuator constraints, particularly for the challenging case of open-loop unstable plants, which are of current interest in flight control. At the same time, due to the low order of the simplified plant models used in flight control it is reasonable to assume full state feedback is available, although the tracked variable is a scalar, e.g., pitch rate. The saturation avoidance aspect of the proposed LQT solution is demonstrated for the simple example.

Actuator Saturation Problem

Physical dynamic systems are commonly modelled as linear systems, whereas in practice, all physical systems are subject to hard (nonlinear) constraints, e.g., and in particular in control systems, actuator displacement and rate saturations. Thus, the impact of these constraints upon the closed-loop feedback control system needs to be addressed.

In well-designed plants the operational requirements have been taken into consideration, and in addition the performance specs that the plant will be expected to meet are in line with the applicable physical constraints. For instance, in flight control the sizing and placement of control surfaces on an aircraft are determined by the performance requirements. Obviously, realistic performance specs must be stipulated. Furthermore, the available control authority must be properly allocated among the tasks at hand. For example, the 23 degrees of available deflection of an elevator of a modern fighter aircraft might be allocated as follows: 4° for stabilization, 2° for differential roll control, 7° for trim, and 10° for maneuvering. Thus, 10° of effector deflection should suffice for the maneuvers that the vehicle is expected to perform. Moreover, an extreme maneuver requiring, say, 12° of effector deflection, will not necessarily result in saturation, as one would have to be unfortunate enough to be simultaneously using all of the remaining control authority for the other tasks. In well-designed plants, then, the aforementioned saturation constraints are generally of minimal impact, and industry has fared well in plant design and closed-loop feedback control.

There are, however, situations where actuator saturation can become a problem in operational flight control systems. For example, dogfights and aerial demonstrations at the boundary of the aircraft's operational envelope may require high-amplitude slewing maneuvers at the extreme edge of an aircraft's capabilities. In the quest for high performance, and when these systems are "pushed to their limits," it is reasonable to expect that actuator saturations may in fact occur, and the consideration of these nonlinear effects in the design phase might indeed reduce the degree of conservativeness of an FCS and thus enhance the FCS performance. Additionally, there is the quest for reconfigurable flight control, which is driven by the need to accommodate failed or battle-damaged control surfaces; saturation of the actuators may realistically become a problem in the event of a control surface failure or when battle damage is sustained, and performance is to be recovered.

Deflection (or displacement) limits are probably the most commonly studied type of actuator saturation, but rate limitations are equally significant, and in practical applications, it transpires, more significant than the former. This has been shown to be the case in our simulation studies. This came as no surprise since, in fact, actuator rate saturations have most recently been implicated in the departure, viz., the onset of unstable oscillations and subsequent crash of a new fighter at an air show [1, 2], and the YF-22 crash landing [7].

Moreover, any type of saturation invalidates, at least to some extent, the otherwise linear and familiar nature of a

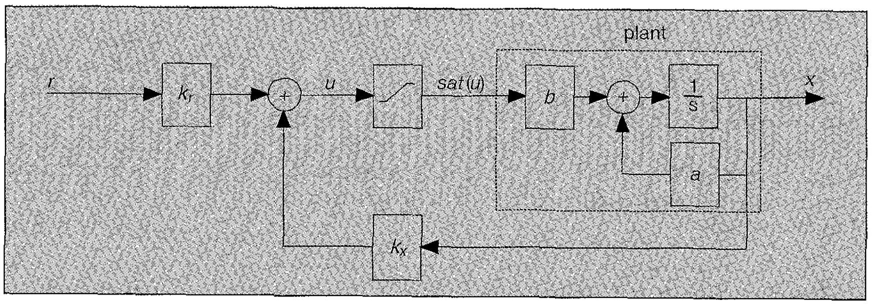

Fig. 1. Closed-loop control system.

linearly designed FCS which employs dynamic compensation; this is colloquially referred to as "integrator windup." Actuator saturation may result in *windup* whenever linear dynamic compensation is used. This translates into degraded performance, limit cycling, and/or closed-loop instability/departure—a litany of adverse effects listed in increasing order of severity. It is important to note that actuators are necessarily located in the inner most control loop and at the plant's input. Hence, during periods of saturation, the plant's output no longer instantaneously affects its input and the system is, roughly speaking, essentially in open-loop operation. It is obvious, then, from this observation that actuator displacement and/or rate saturation is especially dangerous when feedback control is used for stabilization of an unstable plant, e.g., the X-29, JAS 39, and F-16 aircraft, with doubling times in the pitch channel of 0.2, 0.3, and 0.5 seconds, respectively. In many cases, the departure of a piloted vehicle is precipitated by pilot-induced oscillations (PIOs). Now, during periods of actuator saturation, "wound-up" control systems exhibit "abnormal" performance which may confuse the human operator, or pilot, which "closes" the outer-most feedback loop. Thus, the aforementioned PIOs, in systems with both an inner (stabilization) feedback loop and an outer feedback loop where a human operator features, are to some degree an artifact of actuator saturation at the plant input [1, 2, 7, 24]. PIOs of this nature are therefore referred to as *nonlinear PIOs*. In conclusion, actuator saturation (in conjunction with non-minimum phase plant characteristics and sensor noise) restricts the benefits of feedback.

Literature Overview

Actuator saturation is a topic of active research in control theory [3-27]. Many efforts, however, are geared toward either somewhat ad-hoc anti-windup schemes and/or the regulation and set-point control problems, as opposed to tracking control, and thus do not directly apply to maneuvering and manual flight control. Also, most of the work fails to address actuator rate saturation or, for that matter, actuator dynamics. Notable exceptions concerning tracking control are [6, 11, 12, 22, 25], and rate saturation is explicitly considered in References [6, 14, 22]. Additionally, in the tradition of Popov's work [23], where linear controllers are used in tandem with nonlinear plants (and which is not of the actuator saturation avoidance type but which entails a Nyquist analysis of the implications of saturation on stability), most of the current work is restricted to stable open-loop plants. Unstable plants are specifically addressed in [4, 6, 12, 22, 25]. Additionally, by neglecting actuator dynamics altogether, actuator constraints are most often treated as control constraints, whereas, particularly in "high gain" and high bandwidth flight control, actuator dynamics should be included, in which case actuator constraints introduce state constraints into the control problem.

Some of the previous work can be classified as neither anti-windup nor saturation avoidance, but rather as performance enhancement. For example, Horowitz [13] has devised a frequency domain approach to "drive the system out of saturation quickly." This ad-hoc approach proposed for SISO systems entails introducing an additional degree of freedom by placing a linear feedback loop around the saturation element.

When an exogenous reference signal is being considered in the literature, the concept of tracking a less aggressive reference as a means of avoiding saturation is advanced—see, e.g., [6, 8, 11, 22, 25]. Most notable is the *reference governor* concept originally proposed by Kapasouris [14]. The original continuous time developments of the reference governor are computationally complex. Gilbert [8] has greatly improved the implementability of the reference governor concept through the use of maximal output admissible sets, where the state vector is required to remain inside some invariant set which precludes actuator saturation, and with a discrete time formulation achieved a finitely determined, globally BIBO stable control solution [8]. The issue of output controllability has been addressed by Wang and Zachery [27]. We seek alternative methods, which place a higher degree of emphasis on the tracking aspect, effectively avoid actuator saturation, and are readily implementable.

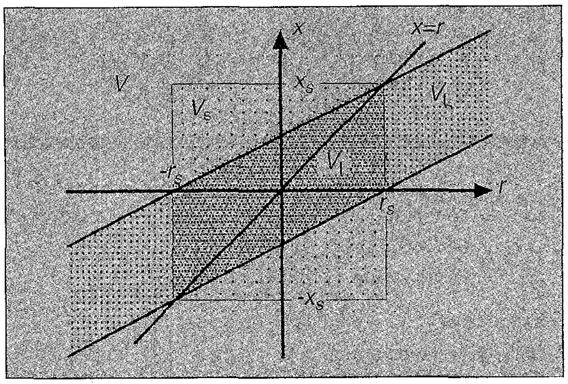

Fig. 2. Sets of interest.

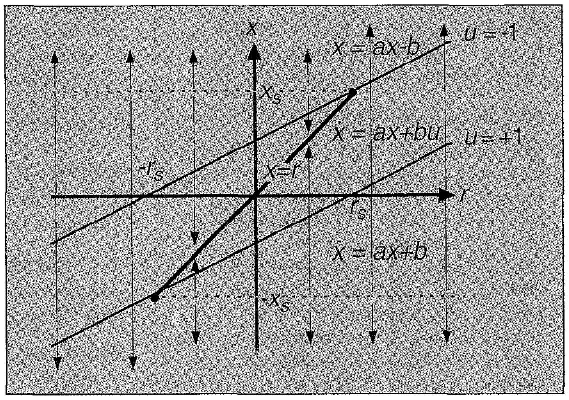

Fig. 3. Stable and unstable equilibria.

A Motivational Example

A scalar, control constrained system is analyzed in order to demonstrate some of the fine points associated with the constrained tracking control problem. The continuous time plant with a constrained control is given by

$$\dot{x} = ax + b \cdot sat(u), \quad x(0) = x_0 \quad (1)$$

where $sat(u)$ is defined

$$sat(u)\begin{cases} -1, & -1 < u \\ u, & -1 \le u \le 1 \\ 1, & u > 1 \end{cases} \quad (2)$$

We are particularly interested in the case of an open-loop unstable plant, thus assume $a > 0$. We desire a state feedback solution which yields tracking, i.e., $x \approx r$, for all $t > 0$, and for "all" exogenous reference signals $r(t)$. Thus, the simplest control within this framework is of the form

$$u = k_x x + k_r r \quad (3)$$

Note that u is in the familiar form $\mathbf{Cx} + \mathbf{Dr}$, and thus actuator constrained problems relate to the example at hand. The linear control law of Equation (3) combined with the open-loop plant of Equation (1) yields the closed-loop block diagram shown in Fig. 1.

The closed-loop system for small control input is thus given by

$$\begin{aligned} \dot{x} &= \left(a + bk_x\right)x + bk_r r \\ &= a_{cl}x + bk_r r \end{aligned} \tag{4}$$

Since perfect tracking should be achieved in steady state, it is clear that

$$bk_r = -a_{cl} \tag{5}$$

and thus

$$k_r = -\frac{a}{b} - k_x \tag{6}$$

Furthermore, due to the control constraint the maximum attainable steady-state (i.e., "statically admissible") value of the state is $|x_S| = b/a$. Also, since the system has been designed for perfect tracking, the maximum steady-state trackable (i.e., "statically admissible") reference signal is $|r_S| = |x_S| = b/a$.

An examination of the relevant two-dimensional space of r and x provides insight into the problem. There are several sets with respect to this augmented space,

$$V = R \times X = \left\{ \mathbf{v} = \begin{bmatrix} r \\ \cdots \\ x \end{bmatrix} \right\} \tag{7}$$

which are of importance—refer to Fig. 2. The set V_L is determined by the control constraint, and consists of the region of the space V in which the closed-loop system (Fig. 1) operates linearly. The set V_S is given by $V_S = R_S \times X_S$, where $R_S = [-r_S, r_S]$ is the set of statically admissible reference values, and $X_S = [-x_S, x_S]$ is the set of statically admissible states. Finally, $V_I \subset (V_L \cap V_S)$ is the maximal invariant set such that for any constant $r = r_\alpha$ and $[r_\alpha, x_0]^T \in V_I$, all subsequent $[r_\alpha, x]^T$ resulting from the closed-loop system dynamics are also in V_I and the control constraint is not violated. In this simple (scalar) case, $V_I = V_S \cap V_L$ (as shown in Fig. 2), but this does not necessarily hold true for higher-order systems.

There are a number of interesting observations that can be made. First of all, there exist trajectories $\mathbf{v} \in V_L$ which are unbounded. That is, r and x can both grow without bound, without violating the constraints. In addition, should the system ever achieve the valid, linear equilibrium $\mathbf{v} = [r_S\ x_S]^T$, the system becomes "stuck." Since these equilibria are repellant (unstable), the state will diverge from them under small perturbations in the directions shown in Fig. 3. Additionally, for any $x \in int(X_S)$, i.e., $-x_S < x < x_S$, there *always* exists a reference trajectory $r(t)$, $r(t) \to 0$, which can bring the state toward the origin without violating the constraints. Conversely, for any $|x| \geq x_S$, the state can *never* be brought back to the origin. (If the open-loop plant were stable, recovery from this state of affairs would be possible, but would entail violations of the control constraints and periods of nonlinear operation, or abandonment of the current control law, e.g., setting $u = 0$). This goes back to our previous observation regarding "open-loop" operation during periods of actuator saturation. This problem just described is illustrated in the diagram shown in Fig. 3.[1] The sign of $\dot{x}$ is indicated by arrows. It is apparent from Fig. 3 that the closed-loop system has stable equilibria points on $int(X_S) = (-x_S, x_S)$, and unstable equilibria at $x = \pm x_S$. Thus, a successful saturation mitigation strategy (SMS) cannot allow $x = \pm x_S$. One could thus define some tolerance $\varepsilon > 0$, and confine x to the set $[-x_S + \varepsilon, x_S - \varepsilon]$. Is the problem solved? Actually, no. As x approaches $\pm x_S$ the amount of available, *stabilizing* control diminishes. Thus, as ε becomes small, the system gets "sticky," with the worst case being getting stuck at $x = \pm x_S$. Whether or not $|r| \leq r_S$ at any given point in time is of little consequence, but ensuring that $x \in int(X_S)$ is crucial. Hence, confining $\mathbf{v}$ to V_I for all time is necessarily conservative from the tracking standpoint, since there exist $[r\ x]^T \notin V_I$ which can be included in the augmented state trajectory (AST) where:

1. The closed-loop system always operates linearly (constraints not encountered);
2. The AST is stable; and,
3. The AST is recoverable (with the specified control law).

Thus, due to the constraints on u, there exist values of r which cannot be tracked linearly. Since u depends linearly on r, the

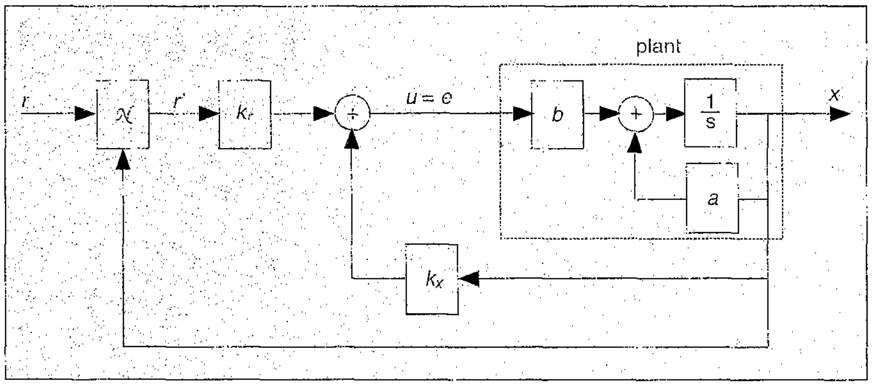

Fig. 4. Transformed closed-loop system.

control constraints are readily transformed into constraints on r, viz.,

$$r_{\min}(x) = -\frac{1}{k_r}(1 + k_x x) \leq r \leq \frac{1}{k_r}(1 - k_x x) = r_{\max}(x) \tag{8}$$

Thus, if prior to input to the control system shown in Fig. 1, the exogenous reference r is modified into an r' which always satisfies the inequality (8), the saturation element becomes transparent, i.e., removing it from the physical system would have no effect. Specifically, in this case, r' is given by

$$r' = \begin{cases} r_{\min}(x), & r < r_{\min}(x) \\ r, & r_{\min}(x) \leq r \leq r_{\max}(x) \\ r_{\max}(x), & r > r_{\max}(x) \end{cases} \tag{9}$$

where $r_{\min}(x)$ and $r_{\max}(x)$ follow from Equation (8).

This transformation of the constraints yields *saturated linear control* (the term "saturated linear control" is chosen because, although linear, the control signal *appears* to be hard limited at the saturation values), which in this particular case provides no compensatory benefit in and of itself. Indeed, the block diagram shown in Fig. 4, where the nonlinear block $\mathcal{N}$ is as defined by Equation (9), is input-output equivalent to the block diagram in Fig. 1. Thus, although the linear system (from r' to x) is BIBO stable, saturation mitigation strategies which solely modify the incoming reference in order to avoid saturation do not necessarily yield an overall BIBO stable control system. Even so, there are some noncompensatory benefits of this transformation, namely, a linear system (from r' to x) ensues, enabling the use of linear analysis methods, saturation avoidance methods can be employed without tinkering inside the innermost (plant stabilizing) control loop, and provided that the nonlinear action $\mathcal{N}$ is not destabilizing, the system is guaranteed to be BIBO stable.

In the more general (and practical) case, where u is subject to some form of

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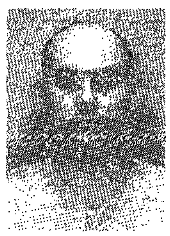

[1]The lines $u = \pm 1$ are shown to intercept the r axis at $\pm r_s$, which is the case only when $a_{cl} = -a$. In general, the r-axis interceptions should be $\pm 1/k_r$, and the x-axis interceptions $\pm 1/k_x$.

dynamics prior to the hard saturation, e.g., actuator dynamics are included, or a dynamic compensation element is used, e.g., integral action, a transformation of the constraints of this type does provide a compensatory benefit, viz., anti-windup, by maintaining consistency between the signals coming into and out of the saturation element. Thus, the element $\mathcal{N}$ in essence removes any dynamics from the inner loop that are susceptible to windup when the control signal is saturated.

Now, an effective control strategy entails replacing the nonlinear block $\mathcal{N}$ of Fig. 4 with a nonlinear element $\mathcal{N}_S$, which not only avoids saturation of the actuator, but also ensures that the *state* maintains statically admissible values. Thus, a modified control signal given by

$$u' = k_x x + k_r r' \qquad (10)$$

where u' not only satisfies the control constraint (Equation (8) is satisfied), but also refrains from driving the state x too close to $bnd(X_S)$. This is accomplished in the nonlinear module $\mathcal{N}_S$, however, without otherwise restricting r'—specifically, the AST is not restricted to V_I. The use of equivalent discrete-time (DT) models lends itself well to this strategy, since subsequent state values are readily determined. In fact, for the scalar case presented here, a one-step-ahead constraint enforcement strategy can be employed in $\mathcal{N}_S$ which guarantees BIBO stability with a minimally conservative control signal.

The above developed nonlinear control concept is illustrated in the following example: Let $a = 1$ (unstable open-loop plant), $b = 2$, and $k_x = -6$ (to obtain good small signal system performance). Then $k_r = 5.5$ (to enforce tracking), and $x_S = r_S = 2$. Also, let $\varepsilon = 0.1$ (the "anti-sticking" coefficient). First, consider the system responses to a pulse command with magnitude 2.4 as shown in Fig. 5. We have purposely chosen a reference signal with magnitude greater than x_S, and therefore it is impossible for the constrained system to track this signal. The unconstrained linear system tracks quite nicely, and good small signal performance is achieved; however, when the control constraint $|u| \leq 1$ is enforced, the response diverges—so much for high amplitude tracking control in open-loop unstable systems where feedback control is used for stabilization. Next, we employ the constraint mitigation strategy just described. It is implemented in discrete-time assuming a zero-order hold on the control signal u and a sample interval T = 0.01 sec. That is, at each time step k, the relaxed reference signal (command) r' is chosen such that $|u_k| \le 1$ and $x_{k+1} \in [-x_s+\varepsilon, x_s-\varepsilon]$. Obviously, even when saturation mitigation is employed, it is impossible for the system to track this reference. Thus, the performance should not be judged on how well the system tracks this reference, rather, how well the system tracks the nearest *feasible* reference, and more importantly, whether a "departure" is avoided, viz., the output is bounded (in other words, whether BIBO stability is achieved). In this particular case, the feasible reference will never converge to a value greater than 1.9, since we are attempting to push the system beyond its limit. The results, shown in Fig. 6, are compared to Gilbert's reference governor (DTRG) implementation [8], which in essence restricts each $[r_k, x_k]^T$ to remain inside the invariant set V_I (reduced accordingly by the parameter ε). The improvement in tracking performance, although modest, is readily apparent (note that the choice ε = 0.1 restricts the maximum output to 1.9 since x_s = 2.0). Not only is the tracking performance improved, but the computational burden is substantially reduced and global stability is not sacrificed. The main difference is that in our approach, $r' > r_s - \varepsilon$ is allowed—see Fig. 6. It should be noted however, that these results are specific to the scalar problem at hand. Indeed, Gilbert's discrete-time reference governor (DTRG) is quite admirable: We merely seek to "squeeze out the last drop" of tracking performance—an issue not directly addressed by the DTRG. However, while BIBO stability is commendable, it is also obvious that attention needs to be given to tracking performance.

Finally, it should be noted that the above results provide a good example of the "sticking phenomenon" discussed previously, as evidenced by the slow convergence of $x(t) \to 0$ after $r(t) = 0$, $t \ge 1$ in Fig. 6—it is apparent from Fig. 6 that an anti-sticking coefficient more on the order of ε = 1.0 would be required in this example to avoid "sticking" altogether. However, increasing ε will reduce the envelope of statically admissible states.

LQT: Tracking Control in the Face of Actuator Saturation

A design methodology that yields high performance, viz., tight (dynamic) *tracking* characteristics, while at the same time *mitigates* the actuator saturation problem is desired. These objectives necessitate the consideration of actuator saturation during the control design process. Hence, nonlinear control design is called for. The two-stage design process consists of a linear (small signal) design with emphasis on the tracking aspect, augmented with a saturation avoidance/mitigation system

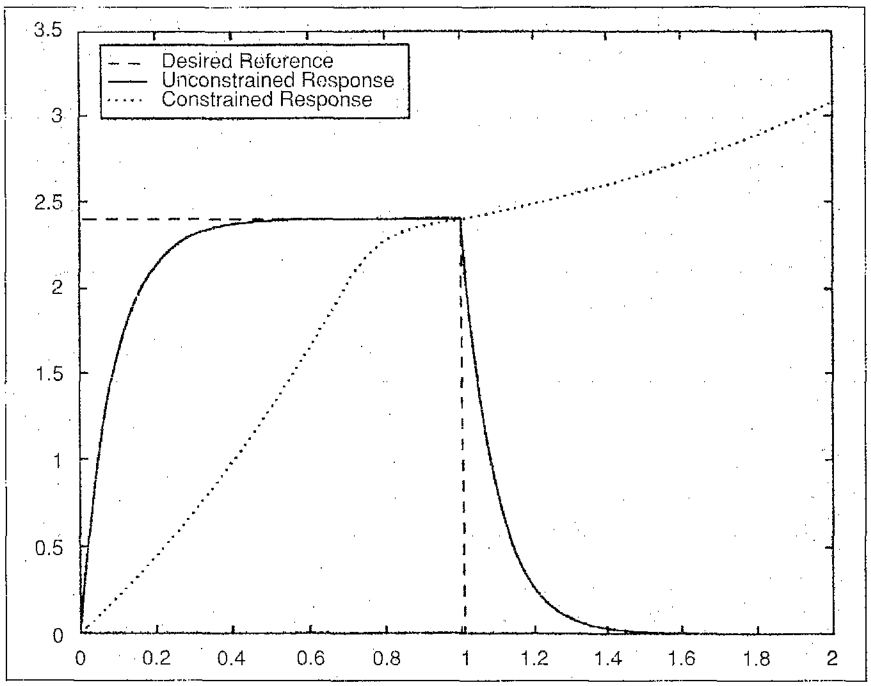

Fig. 5. Unmitigated system responses.

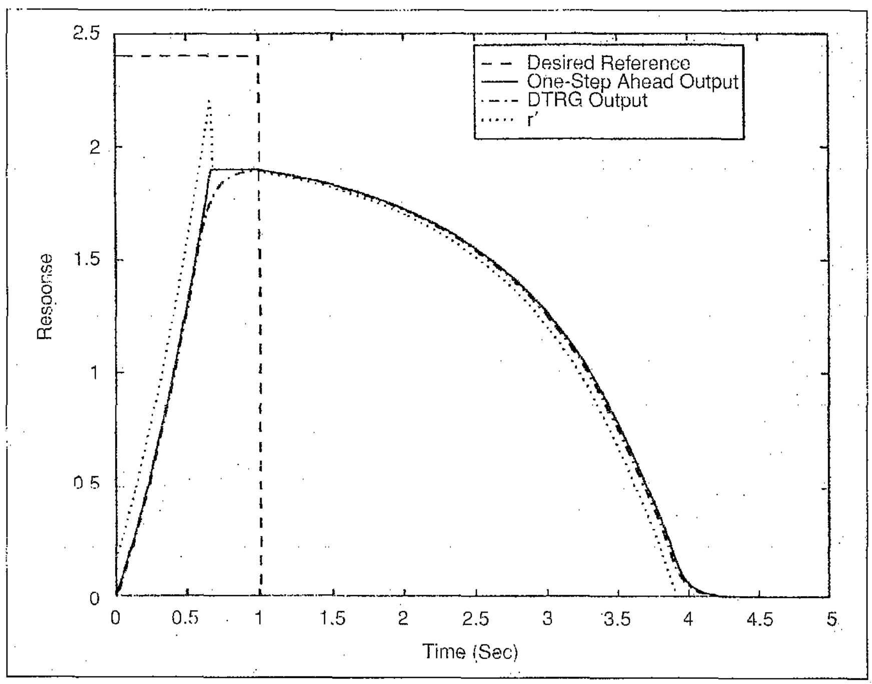

Fig. 6. Scalar example results with saturation mitigation.

(SAMS) to minimize the impact of the actuator constraints. Ideally, the completed system preserves the small signal performance of the linear design (i.e., the SAMS is transparent when the constraints are not active), is not overly complicated, and is implementable in real time. Additionally, the SAMS should not be destabilizing.

Based on the insights from the previous example, an approach to the manual tracking problem for open-loop unstable plants with rate and amplitude constrained dynamic actuators, and utilizing full state feedback and a linear quadratic predictive control strategy is pursued in [16]. Optimal control methods afford the ability to place a high degree of emphasis on the tracking aspect of the problem, but in order to employ optimal control methods, the reference signal must be known in advance. Since this is not possible in the manual tracking problem, a receding horizon approach based on short-term predictions of the pilot's reference is employed. Prediction methods are thoroughly investigated, and it is shown in [16] that tracking performance is improved over regulator-based tracker designs. This approach is preferrable to the behavioral assumptions driven LQG or "internal model" approaches. Now, subsequent to each of these short-term predictions, a feasible reference signal which is *close* to the (predicted) pilot reference is determined based on prespecified *feasibility criteria* which include (a) saturation avoidance, (b) static admissibility, and/or invariance principles. The tradeoffs between tracking performance, stability, and computational requirements are explored. Dynamic actuator models are included, thus facilitating the proper incorporation of actuator rate constraints into the problem, in addition to the more commonly addressed amplitude constraints. When simple extrapolation algorithms are employed, the LQT solution is in the form of Equation (10), the constraint enforcement strategy is similar to the one employed in the previous example, and the results are in line with those shown in Fig. 6. Naturally, when more sophisticated prediction methods are used, the LQT control signal depends additionally on previous values of the reference input.

Consider for example, the longitudinal model of an F-16 derivative at the flight condition 10,000 ft, Mach 0.7. An integral control state, $z_{k+1} = z_k + T(r_{k+1}-y_{k+1})$, where $T = 0.01$ is the sample interval, is included, and thus the "open-loop" plant model is given by

$$\begin{bmatrix} \alpha_{k+1} \\ q_{k+1} \\ \delta_{k+1} \\ z_{k+1} \end{bmatrix} = \begin{bmatrix} 0.9887 & 0.0098 & -0.0025 & 0 \\ 0.0368 & 0.9877 & -0.1756 & 0 \\ 0 & 0 & 0.8187 & 0 \\ -0.000368 & -0.009877 & 0.001938 & 1 \end{bmatrix} \begin{bmatrix} \alpha_k \\ q_k \\ \delta_k \\ z_k \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0.1813 \\ 0 \end{bmatrix} \delta_{c_k} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0.01 \end{bmatrix} r_{k+1}$$

where α (rad) is angle of attack, q (rad/sec) is pitch rate, δ (rad) is elevator deflection, and z is the integral control state mentioned previously. Furthermore, the elevator is subject to the constraints

$$-0.37 \le \delta_{k+1} \le 0.37$$
$$-0.01 \le \delta_{k+1} - \delta_k \le 0.01, \quad k = 0, 1, \ldots$$

The LQT control method, employing a two-stage polynomial reference prediction strategy and a planning horizon of $N = 15$, combined with a one-step-ahead constraint enforcement strategy based on the transformation of constraints as illustrated in the previous example, yields the control law

$$u_k = \delta_{c_k} = \mathbf{k}_x^T \mathbf{x}_k + \mathbf{k}_r^T \begin{bmatrix} r_k & r_{k+1} \end{bmatrix}^T + k_{r'} r'_{k+1}$$

where the precomputed and fixed gains $\mathbf{k}_x^T = \begin{bmatrix} 0.2013 & 0.7317 & -0.5686 & -4.007 \end{bmatrix}$, $\mathbf{k}_r^T = \begin{bmatrix} 5.2366 & -5.6107 \end{bmatrix}$, and $k_{r'} = -0.4197$. The response is compared to an LQR-based tracker with control law given by $u_k = \delta_{c_k} = -\left(r_{k+1} + \mathbf{k}_{LQR}^T \mathbf{x}_k\right)$, where

$$-\mathbf{k}_{LQR}^T = \begin{bmatrix} 0.3509 & 1.1373 & -0.9183 & -6.6107 \end{bmatrix}$$

and saturation mitigation is not employed, in Fig. 7.

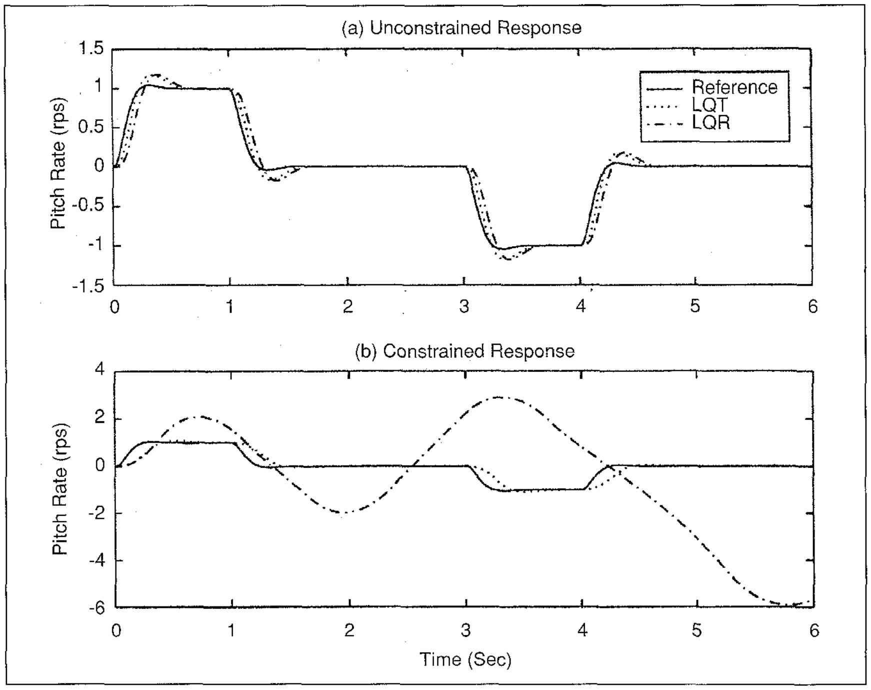

Fig. 7. *Longitudinal F-16 model simulation results.*

Conclusion

Manual tracking control in the presence of constrained dynamic actuators is a rich problem. It has been demonstrated that even the simplest tracking control problem is somewhat complex. Future research that places a high degree of emphasis on the tracking aspect of the problem, while at the same time mitigates the impact of these actuator rate and amplitude constraints, and particularly for the challenging case of open-loop unstable plants, is warranted. These issues, particularly for the dynamic tracking problem (as opposed to the regulator problem), and which lie at the heart of manual flight control, have not been adequately addressed to date. A novel time-domain tracking control approach, LQT, using an on-line optimization strategy that directly addresses both rate and displacement saturation is proposed. Also, because actuator rate saturations have been known to contribute to the onset of pilot-induced oscillations, the LQT saturation effects mitigation approach implicitly addresses the nonlinear PIO problem.

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Editor's Note: The following contribution to "Control Systems Art" (see the February 1996 issue for "Lumas O. Nortoc," alias "Root Locus Man," in SAMPLED DATA) was sent in by Mr. Joel Jensen and Prof. Chin S. Hsu, School of Electrical Engineering and Computer Science, Washington State University. This particular piece of root locus art is titled "The Infamous Root Locus Alien." Your Editor reproduced this root locus in Matlab, using the poles and zeros as shown.

System Zeros	System Poles
$-5.0 \pm j5.0$	$-4.3 \pm j1.8$
$-4.3 \pm j1.8$	$-0.15 \pm j0.8$
$-0.35 \pm j0.2$	$\pm j0.3$
$\pm j2$	$0.4 \pm j0.3$
$\pm j2$	$0.45 \pm j0.6$
0.7	$1.0 \pm j1.3$
0.7	$1.0 \pm j1.3$
$1.0 \pm j1.5$	$2 \pm j0.15$
$1.0 \pm j1.5$	2
2.2