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Nonovershooting multivariable tracking control for time-varying references

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Abstract— **We consider the classic problem of exact output regulation for a linear time invariant plant. Under the assumption that a state feedback output regulator exists, we adapt the design methods of Schmid and Ntogramatzidis [1] to obtain a regulator that will track a time-varying reference without overshoot in the transient response.**

I. Introduction

The problem of output regulation is central to modern control theory. The basic problem considers a multivariable linear time invariant (LTI) plant which is desired to track a known reference signal. The reference signals are modeled by an independent exosystem. The aim of the problem is to design a feedback controller which internally stabilises the plant and ensures the output converges asymptotically to the desired reference signal. The problem has a long history, and extensive compilations of results are given in [2] and [3].

Much of the literature has concentrated on the tracking of step references. For continuous time systems, in [4] it was shown how to design a two parameter feedback controller for an LTI plant that renders the step response nonovershooting. In [5] an eigenstructure assignment method was proposed to obtain a nonovershooting LTI state feedback controller for plants with one nonminimum phase zero. In [6] conditions are given for the existence of a controller to achieve a sign invariant impulse response, and hence also a nonovershooting step response. A common limiting feature of these papers is that they considered strictly proper SISO systems, and that the system state is assumed to be initially at rest.

These two latter limitations were overcome in [1], where MIMO systems were considered. The authors gave a linear state feedback control to design a nonovershooting controller for a step reference. The method was applicable to both square and non-square systems, minimum phase and nonminimum phase systems, strictly proper and non-strictly proper systems, and did not assume that the initial state of the system is at rest. In [7] the design method of [1] was modified to achieve a step response for MIMO systems that is both nonovershooting and nonundershooting.

There have been but few papers addressing the problem of obtaining good transient response performance in the tracking of time varying references. [8] employed the composite nonlinear feedback (CNF) technique of [9]-[10] and adapted it to the tracking of a general reference signal generated by an exosystem. The authors offered methods for designing the nonlinear CNF term in the control law that would improve the transient performance of a linear controller, but did not guarantee the avoidance of overshoot.

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In this paper we seek to adapt the multivariable design method of [1] to the problem of exact output regulation. We assume the problem of output regulation by state feedback is solvable, i.e. there exists a linear state feedback controller that internally stabilizes the plant and achieves output regulation. In this case we show that if there exists a state feedback controller that yields a nonovershooting response for a step reference, then a state feedback output regulator can be obtained to deliver a nonovershooting output regulation. To the best of the authors' knowledge, this is the first design method that achieves multivariable exact output regulation with a nonovershooting (or nonundershooting) transient response.

The paper is organised as follows: In Section 2 we introduce the classic problems of exact output feedback and discuss its solvability with respect to state feedback. We also review the nonovershooting state feedback design methods of [1]. In Section 3, we consider a plant with exosystem and, under the assumption that exact output regulation is achievable, we offer conditions under which a nonovershooting transient response can be achieved with linear state feedback. In Section 4, we apply the method to the XY-table simulation given in [8]. We develop a state feedback law that allows the XY-table to draw a circle, with trajectory starting from the origin. Unlike the CNF control law employed in that paper, our method succeeds in drawing the circle without overshoot. This means that the trajectory remains within the circle at all times. This is achieved without slowing the response time, or using larger control amplitude than that of the CNF controller. Finally Section 5 offers some concluding remarks.

Definitions and Notation: The symbol 0_n represents the zero vector of length n, and I_n is the n-dimensional identity matrix. For a square matrix A, we use $\sigma(A)$ to denote its spectrum. We say that a square matrix A is *Hurwitz-stable* if $\sigma(A)$ lies within the open left-hand complex plane, and it is *anti-Hurwitz-stable* if $\sigma(A)$ lies within the open right-hand complex plane. A pair (A,B) is *stabilizable* if there exists a state feedback matrix F such that $A+BF$ is Hurwitz-stable.

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II. PROBLEM FORMULATION

We consider a linear multivariable plant ruled by the equation

$$\Sigma : \begin{cases} \dot{x}(t) &= A\,x(t) + B\,u(t) \\ y(t) &= C_y\,x(t) + D_y\,u(t) \\ z(t) &= C\,x(t) + D\,u(t) \end{cases} \tag{1}$$

where, for all $t \geq 0$, the signal $x(t) \in \mathbb{R}^n$ represents the state, $u(t) \in \mathbb{R}^m$ represents the control input, $y(t) \in \mathbb{R}^p$ represents the measured output, $z(t) \in \mathbb{R}^q$ represents the controlled output, $r(t) \in \mathbb{R}^\rho$ represents a reference signal, as shown in Figure 1. All the matrices appearing in (1) are appropriate dimensional constant matrices.

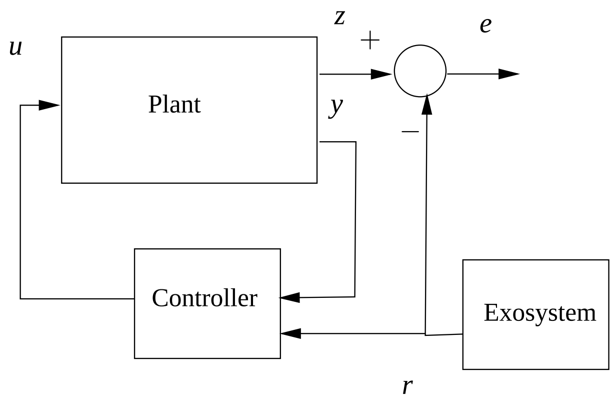

Fig. 1. Output feedback control architecture

The reference input r is generated by an autonomous exosystem ruled by

$$\Sigma_{exo} : \begin{cases} \dot{w}(t) &= S\,w(t), \quad w(0) = w_0 \\ r(t) &= L\,w(t) \end{cases} \tag{2}$$

where, for all $t \geq 0$, $w(t) \in \mathbb{R}^{n_1}$, and S and L are also appropriate dimensional constant matrices. We assume that all the eigenvalues of S are anti-Hurwitz-stable, i.e., they all have non-negative real part. This assumption does not cause any loss of generality, see [3, p. 18]; indeed, if the closed-loop system (excluding the exosystem) is internally stable, the vanishing modes of the exosystem do not affect the regulation of the output. We also assume that the states of the exosystem are measurable, i.e., they are available to be used to generate a feedforward action in the control law.

We design a controller with measurement signal y which generates the control input signal u. Our design objective is for the reference signal r to be asymptotically tracked by the output z of the system. As such, by defining the error signal

$$e(t) \stackrel{\text{def}}{=} z(t) - r(t),$$

our objective is to achieve $\lim_{t\to\infty} e(t) = 0$. We then consider a new system Σ_e obtained from Σ by considering the new output e instead of z:

$$\Sigma_e : \begin{cases} \dot{x}(t) &= A\,x(t) + B\,u(t), \; x(0) = x_0 \\ y(t) &= C_y\,x(t) + D_y\,u(t) \\ e(t) &= C_e\,x(t) + D_{eu}\,u(t) - r(t) \end{cases}$$

By defining $D_{ew} = -L_2$, we can re-write Σ_e as

$$\Sigma_e : \begin{cases} \dot{x}(t) &= A\,x(t) + B\,u(t), \; x(0) = x_0 \\ \dot{w}(t) &= S\,w(t), \; w(0) = w_0 \\ y(t) &= C_y\,x(t) + D_y\,u(t) \\ e(t) &= C_e\,x(t) + D_{eu}\,u(t) + D_{ew}\,w(t) \end{cases} \tag{3}$$

In order to simplify the derivations of the tracking control law, we assume $D_y = 0$. This assumption does not lead to a significant loss of generality, as shown in [3, p. 16]. For design purposes we will also consider the *nominal plant* Σ_{nom} which arises when the exosystem is excluded from consideration. In this case Σ_e simplifies to the homogenous system

$$\Sigma_{nom} : \begin{cases} \dot{\tilde{x}}(t) &= A\,\tilde{x}(t) + B\,\tilde{u}(t), \; \tilde{x}(0) = \tilde{x}_0 \\ \tilde{e}(t) &= C_e\,\tilde{x}(t) + D_{eu}\,\tilde{u}(t) \end{cases} \tag{4}$$

For this system, the problem of exact output regulation consists of driving the system state to the origin from some arbitrary non-zero initial condition. Next we briefly revisit some classic results on output regulation by state feedback. The discussion that follows is based on [3, Chapter 2]. We will only consider the continuous-time case. We note however that [1] also considered discrete-time systems, and the results presented here can be adapted to the discrete-time case with only minor modifications.

A. Output regulation with state feedback

In the case where the controller has access to the state of the system, as well as to the reference and the disturbance, we have $p = n$, $C_y = I$ and $y = z$. The control input has the form

$$u(t) = F\,x(t) + G\,w(t), \tag{5}$$

which is given by a static state-feedback component $F x(t)$ and a static feedforward component $G\,w(t)$ that uses the state of the exosystem. The closed-loop system is

$$\Sigma_{cl} : \begin{cases} \dot{x}(t) &= (A + B\,F)\,x(t) + B\,G\,w(t), \\ \dot{w}(t) &= S\,w(t), \\ e(t) &= (C_e + D_{eu}\,F)\,x(t) + D_{ew}\,G\,w(t) \end{cases} \tag{6}$$

Definition 2.1: (a) A state feedback controller u of the form (5) is said to achieve *exact output feedback regulation* if both the following conditions hold

(I) Internal Stability: The system $\dot{x}(t) = (A + B\,F)\,x(t)$ is asymptotically stable, and

(II) Output Regulation: For all $x_0 \in \mathbb{R}^n$, and $w_0 \in \mathbb{R}^{n_1}$, the closed-loop system Σ_{cl} satisfies $\lim_{t\to\infty} e(t) = 0$.

(b) For a given initial condition (x_0, w_0) of Σ_e, the control law u in (5) is said to achieve *nonovershooting exact output feedback regulation* for Σ_e from (x_0, w_0) if the output e of Σ_{cl} vanishes without changing sign in any component, i.e., for each $i \in \{1, \ldots, p\}$, $e_i \to 0$ and $\text{sgn}(e_i(t))$ is constant for all $t \geq 0$. Finally, we say the controller achieves *globally nonovershooting exact output feedback regulation* if e is nonovershooting from all initial conditions (x_0, w_0).

The following theorem gives conditions under which exact output feedback regulation can be achieved by a state feedback control law of the form (5).

Theorem 2.1: ([3], Theorem 2.3.1) Assume system Σ_e in (3) satisfies the following assumptions

A.1 The pair (A, B) is stabilizable.

A.2 The matrix S is anti-Hurwitz-stable.

A.3 There exists matrices Γ and Π satisfying

$$\Pi\, S = A\,\Pi + B\,\Gamma \quad (7)$$

$$0 = C\,\Pi + D\,\Gamma + D_{ew} \quad (8)$$

Let F be any matrix such that $A + B\,F$ is Hurwitz-stable, and let $G = \Gamma - F\,\Pi$. Then u as in (5) achieves exact output feedback regulation for Σ_e.

These two equations (7)-(8) are known as the *regulator equation*. Solvability conditions are given in [3, Chapter 2].

B. Nonovershooting and nonundershooting tracking controller design methods

The paper [1] gave several methods for the design of a linear state feedback control law to deliver a nonovershooting step response for systems in the form Σ_{nom}, and [7] extended the design methods to deliver a nonundershooting step response system, and also a monotonic step response. Our aim in this paper is to consider how these methods may be employed to achieve exact output regulation with a nonovershooting (or nonundershooting) transient response. We now briefly review these methods.

The design methods assume the system Σ_{nom} is a square system ($m = p$) and at time $t = 0$ is at a known initial equilibrium (u_o, x_0, y_0). The closed loop poles are to be selected from within a user-specified interval $[a, b]$ of the negative real line. The algorithm selects candidate sets $\mathcal{L}$ of distinct closed-loop eigenvalues within the specified interval and then associates them with candidate sets of eigenvectors $\mathcal{V}$ and eigendirections $\mathcal{W}$. These are obtained in terms of the system matrix pencil

$$P_\Sigma(s) \stackrel{\text{def}}{=} \begin{bmatrix} A - sI_n & B \\ C & D \end{bmatrix} \quad (9)$$

in such a way that only a small number of the closed-loop modes contribute to each output component. The error function $e(t)$ is then formulated in terms of the candidate set of eigenvectors and a test is used to determine if the system response is nonovershooting in all components. If the test is not successful, then a new candidate set $\mathcal{L}$ is chosen, and the process is repeated. If it succeeds, then the desired matrix F can be obtained by applying Moore's algorithm [11] to the sets $\mathcal{V}$ and $\mathcal{W}$. The tests are analytic in nature, and do not require simulating the system response to test for overshoot.

Recently the design method of papers [1] and [7] was incorporated into a public domain MATLAB® toolbox, known as **NOUS** [12]. The toolbox asks the user to specify their LTI system in state space form, together with a specified initial condition and desired step reference. The user is also asked to nominate a subinterval $[a, b]$ of the negative real line within which the poles of the closed loop system are to be located. The **NOUS** algorithm then seeks to obtain a gain matrix that will deliver closed-loop poles within the specified interval, and also a nonovershooting step response.

The method exploits any minimum phase invariant zeros the system may have; these modes are then chosen among the closed-loop poles and rendered invisible at the outputs via pole/zero cancelation. Extensive testing by the authors of [12] has shown the search method is likely to be successful if the number of system states, less the number of minimum phase zeros, is not more than three times the number of control inputs, i.e. the inequality

$$n - z \leq lp \quad (10)$$

holds true for some $l \leq 3$, where z is the number of minimum phase zeros. Interestingly, the presence of non-minimum phase zeros does not negatively impact upon the success of the search. In the paper [13], the **NOUS** algorithm was used to obtain nonovershooting (and nonundershooting) responses to systems with real nonminimum phase zeros. Moreover, the search algorithm can sometimes be successful even where (10) requires $l = 4$ or more. Current research by the authors of [1] is aimed at obtaining analytic conditions in terms of the system structure that are necessary and sufficient to guarantee the existence of a state feedback controller that will deliver the desired transient response.

III. Nonovershooting and nonundershooting output Regulation

In this section we present the main results of our paper. We extend the classic problem of output regulation to also consider the design of linear control laws of the form (5), to deliver a desirable transient response. Specifically, we consider the problem of choosing the control laws for Σ_e such that e is nonovershooting, for any given (x_0, w_0). Our main result indicates that if we can obtain a state feedback control law $\tilde{u}(t) = F\,\tilde{x}(t)$ that achieves nonovershooting exact output feedback regulation for Σ_{nom}, then the state feedback law u in (5) with this F will achieve nonovershooting exact output feedback regulation for Σ_e.

Theorem 3.1: Let (x_0, w_0) be any initial condition for Σ_e in (3). Assume that (A.1)-(A.2) hold and that Π and Γ satisfy (7)-(8). Assume there exists F such that $\tilde{u}(t) = F\,\tilde{x}(t)$ yields nonovershooting exact output feedback regulation for Σ_{hom} from initial condition $\tilde{x}_0 = x_0 - \Pi\, w_0$, and let $G \stackrel{\text{def}}{=} \Gamma - F\,\Pi$. Then u in (5), with this F and G, yields nonovershooting exact output feedback regulation for system Σ_e from the initial condition (x_0, w_0).

Proof: The closed-loop system arising from applying $\tilde{u} = F\,\tilde{x}$ to Σ_{nom} is

$$\begin{cases} \dot{\tilde{x}}(t) = (A + B\,F)\,\tilde{x}(t), \quad \tilde{x}(0) = \tilde{x}_0 \\ \tilde{e}(t) = (C_e + D_{eu}\,F)\,\tilde{x}(t) \end{cases} \quad (11)$$

and by assumption we have $\tilde{e} \to 0$ without overshoot. Next we consider Σ_e and introduce the change of coordinates $\xi(t) = x(t) - \Pi\, w(t)$. Then $\xi(0) = x(0) - \Pi\, w(0) = \tilde{x}_0$. We obtain

$$\begin{aligned}\dot{\xi}(t) &= \dot{x}(t) - \Pi\dot{w}(t) \\ &= \dot{x}(t) - \Pi S w(t) \\ &= (A+BF)x(t) + (B(\Gamma - F\Pi) - \Pi S)w(t) \\ &= (A+BF)x(t) - (A+BF)\Pi w(t), \quad \text{using (7)} \\ &= (A+BF)\xi(t). \qquad (12)\end{aligned}$$

Also

$$\begin{aligned}& (C_e + D_{eu}F)x(t) + (D_{eu}(\Gamma - F\Pi) + D_{ew})w(t) \\ =\ & (C_e + D_{eu}F)x(t) + (D_{eu}\Gamma - D_{eu}F\Pi + D_{ew})w(t) \\ =\ & C_e x + D_{eu}F(x(t) - \Pi w(t)) + (D_{eu}\Gamma + D_{ew})w(t) \\ =\ & C_e\xi(t) + D_{eu}F\xi(t) + (C_e\Pi + D_{eu}\Gamma + D_{ew})w(t) \\ =\ & (C_e + D_{eu}F)\xi(t) \qquad (13)\end{aligned}$$

by (8). Hence the closed loop system arising from Σ_e under u in (5) with initial condition (x_0, w_0) is

$$\left\{ \begin{array}{rcl} \dot{\xi}(t) &=& (A+BF)\,\xi(t), \quad \xi(0) = \xi_0, \\ e(t) &=& (C_e + D_{eu}F)\,\xi(t) \end{array} \right. \qquad (14)$$

which is identical to (11), and so $e \to 0$ without overshoot. Hence u achieves nonovershooting exact output regulation for Σ_e from (x_0, w_0). ■

Remark 3.1: The significance of Theorem 3.1 is that if the exact output regulation of Σ_e can be achieved by state feedback, then the design methods of [1] can be utilised to obtain nonovershooting exact output regulation. It is an immediate corollary to Theorem 3.1 that if $\tilde{u} = F\tilde{x}$ delivers a nonundershooting, or monotonic, step response for Σ_{nom}, then u with this same F will deliver nonundershooting, or monotonic, output regulation for Σ_e.

IV. EXAMPLE

Example 4.1: In [8], the authors considered an application of the generalized CNF (Composite nonlinear feedback) technique to the trajectory tracking control of an XY-table. A pencil attached to the mover of the XY-table is constrained to move along the x-axis and y-axis of the table and draw any desired 2-D trajectory onto the paper underneath.

Precision control of an XY-table is an important problem in manufacturing, and transfer functions for the linear relation between the x and y components of the motion and the corresponding motor input currents for the table used in [8] were given in [14]. Representing these in state space form and combining them as two decoupled SISO systems yields a MIMO system Σ_1 in the form (1) with

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -2.825 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -3.226 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 8.034 & 0 \\ 0 & 0 \\ 0 & 6.774 \end{bmatrix}$$

$$C_e = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}, \; D_{eu} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The control inputs have saturation amplitudes of 1 A, and the output displacements are measured in metres. The authors of [8] considered the tracking of two sinusoidal references

$$\begin{aligned} r_x &= 0.1\cos(.4\pi t) \\ r_y &= 0.1\sin(.4\pi t) \end{aligned}$$

Thus the problem is for the pencil to draw a circle, commencing from the origin in xy-coordinates. This reference signal may be generated by the exosystem Σ_{exo} in (2) with

$$S = \begin{bmatrix} 0 & 1 & 0 & 0 \\ -\omega^2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\omega^2 & 0 \end{bmatrix}, \; \omega(0) = \begin{bmatrix} 0.1 \\ 0 \\ 0 \\ .1\omega \end{bmatrix}$$

$$L = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

where $\omega = 0.4\pi$. The authors of [8] used the CNF technique to design separate SISO state feedback control laws for the x and y subsystems. The results were shown in Figures 7 and 9 of that paper. The CNF controller was successfully able to track both sinusoids, leading to a circular trajectory being drawn on the XY-table. The authors noted that their simulation results showed that their generalized CNF control yielded better tracking performance than a PID controller. However, the CNF trajectory did exhibit overshoot of approximately 5% in the x-coordinate, and 15% in the y-coordinate.

We used the **NOUS** toolbox to design a linear state feedback controller for the nominal system Σ_{nom} in (4). The system has no invariant zeros, $n = 4$ states and $m = p = 2$ control inputs and outputs. Thus it satisfies (10) with $l = 2$, and hence a successful search was anticipated. We sought to obtain closed loop poles within the interval $[-8, -10]^T$, in order to obtain a response time similar to those of the linear component of the CNF control law, and hence also use similar control input amplitudes. The search was indeed successful, requiring only a few milliseconds of runtime. The control law obtained is

$$F = \begin{bmatrix} -9.1413 & -1.7818 & 0 & 0 \\ 0 & 0 & -12.9452 & -2.2944 \end{bmatrix}$$

yielding closed-loop poles $\mathcal{L} = \{-8.5105, \; -8.6294, \; -8.7749, \; -9.9934\}$. Solving (7)-(8) for Σ_1 yields

$$\Pi = I_4, \; \Gamma = \begin{bmatrix} -0.1966 & 0.3516 & 0 & 0 \\ 0 & 0 & -0.2331 & 0.4762 \end{bmatrix}$$

and finally

$$G = \begin{bmatrix} 8.9447 & 2.1334 & 0 & 0 \\ 0 & 0 & 12.7121 & 2.7706 \end{bmatrix}$$

Then applying the control law u in (5) to Σ_1 yields system outputs (x, y), reference signals (r_x, r_y), and tracking errors (e_x, e_y) shown in Figure 2. We observe that, in contrast with the CNF controller performance given in [8], neither the x nor the y component overshoot their reference signals.

The control inputs (u_x, u_y) are shown in Figure 3. Both control input amplitudes remain less than the saturation

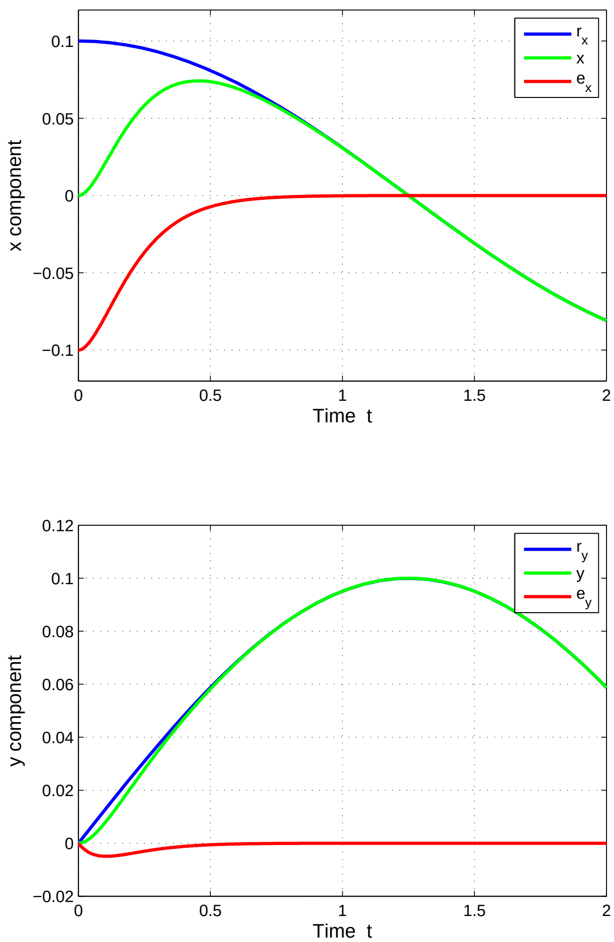

Fig. 2. System outputs, references and tracking errors for Σ_1 using F.

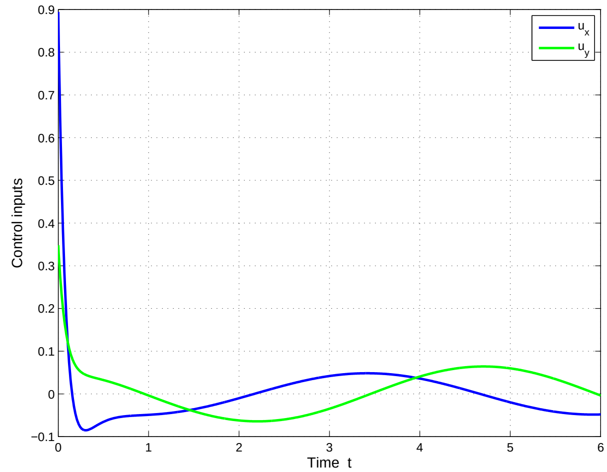

Fig. 3. Control inputs for Σ_1 using F.

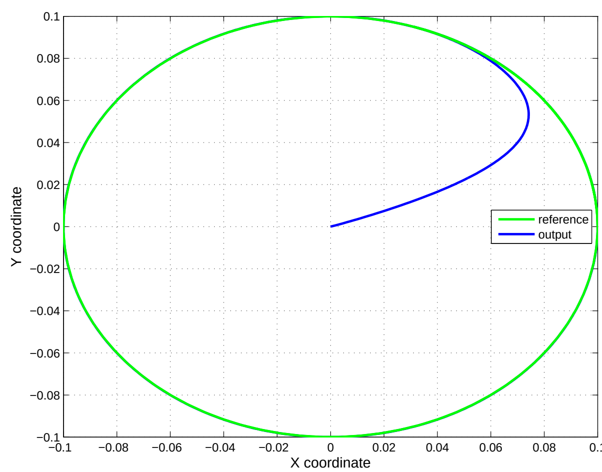

Fig. 4. The drawn circle using F.

constraint of $1\ A$, and lie within the range of $-0.1\ A$ to $0.3\ A$ for most of the transient, similar to those shown in Figure 7 of [8]. The settling times in both components are of about 0.5 seconds, approximately equal to those in [8].

When the outputs are drawn in xy-coordinates, simulating the trajectory of the pencil on the XY table, we obtain the curves in Figure 4. We observe the trajectory of the pencil asymptotically approaches the circle circumference without ever going outside of it. This is in contrast with the trajectory shown in Figure 9 of [8], which showed that under CNF control, the pencil trajectory went outside the circle.

The state feedback controller of [8] was implemented with a reduced order observer. In [15] it was shown that the design method of [1] for tracking a constant step reference could be successfully implemented in conjunction with full and reduced order observers. This was extended to the tracking of time-varying references with dynamic measurement feedback in [16]. Provided the initial observer error is sufficiently small, the nonovershooting properties of full state feedback control are preserved. In the present example, the initial states of the augmented system (namely the plant and exogenous reference generators) are known precisely. As the **NOUS** method uses a linear controller, by the Separation Principle, we know that the outputs obtained using an observer scheme are identical to those observed when state feedback alone are used, since the observer dynamics are zero. Consequently in the present simulation we did not implement the state feedback law in conjunction with an observer.

The example simulations give further insight into the performance of the CNF technique implemented in [8]. In that paper the authors compared their performance against a PID controller and used the improved performance to justify the use of their nonlinear technique. The present example shows that superior transient performance can in fact be obtained with a linear controller, when the design method of [1] is used to obtain the gain matrix for the state feedback law.

V. CONCLUSION

We have revisited the design method for a linear state feedback tracking controller given in [1] within the output regulation framework to extend it to accommodate the nonovershooting tracking of time-varying signals. The output regulation framework can also be used for the asymptotic rejection of known time-varying disturbances; further details are provided in [16]. Examples were given to show that the design method can offer superior transient performance to the CNF method of [8]. To the best of the authors knowledge, this paper presents the first linear control scheme for the tracking of time-varying signals without overshoot.

VI. ACKNOWLEDGEMENTS

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