Robust Control For Underwater Vehicle Systems With Time Delays

Michael S. Triantafyllou and Mark A. Grosenbaugh

Abstract—**Presented in this paper is a robust control scheme for controlling systems with time delays. The scheme is based on the Smith controller and the LQG/LTR (Linear Quadratic Gaussian/Loop Transfer Recovery) methodology. The methodology is applicable to underwater vehicle systems that exhibit time delays, including tethered vehicles that are positioned through the movements of a surface ship and autonomous vehicles that are controlled through an acoustic link. An example, using full-scale data from the Woods Hole Oceanographic Institution's tethered vehicle ARGO, demonstrates the developments.**

I. Introduction

Continuous exploration of the ocean bottom requires reliable equipment to withstand the hostile environment. Tethered vehicles offer such reliable operation, because the surface-support ship can be used to position the underwater vehicle, thus reducing considerably the complexity of the underwater system. Autonomous vehicle systems that are controlled through an acoustic link offer the potential for reliable operation, because most of the hardware of the control system can be placed onboard a support ship or on land.

In either case, time delays are present in the control action. For vehicles controlled through a long tether, the time delay is caused by the slow propagation of transverse motions in the tether, and it can reach values of 1 to 2 min for a 1000-m cable, and 5 min for a 6000-m cable (Fig. 1). For autonomous vehicles controlled through an acoustic link, the delay is caused by the finite sound speed of water.

Control in the presence of time delays poses particular difficulties, since a delay places a limit on the achievable response speed of the system. Also, assessing the robustness of the closed-loop system to modeling errors, particularly errors in the time-delay constant, becomes of paramount importance.

A scheme to design controllers with guaranteed nominal stability for plants involving delays is shown in Fig. 2 and is known in the literature as the Smith controller [1]. Attention has been paid to this scheme over the years and some of its properties have been reported in [2]-[9].

Optimal control methods are well developed for linear, time-invariant, finite-dimensional systems. Recent progress in the design of robust control schemes has resulted in the Linear Quadratic Gaussian (LQG) methodology with Loop Transfer Recovery (LTR), referred to in the sequel as the LQG/LTR methodology [10], [11].

What will be shown here is how the Smith control scheme can be combined with the LQG/LTR methodology to achieve robust control designs. An example is presented for a tethered underwater vehicle system, although the implementation steps would be the same for an acoustically controlled autonomous vehicle system.

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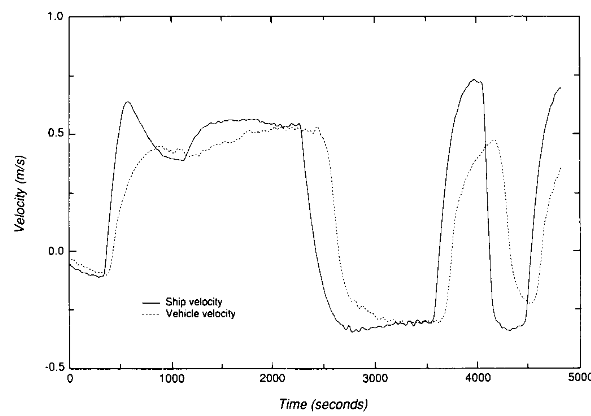
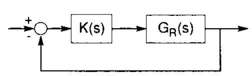
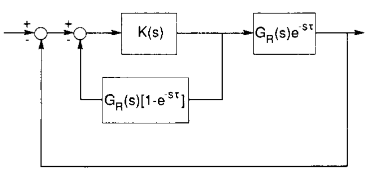


Fig. 1. Ship velocity and vehicle velocity as function of time (full-scale measurements, tether length equals 1200 m).



(a)



(b)

Fig. 2. Block diagram of the classical Smith control loop showing: (a) Reduced loop, and (b) auxiliary loop.

II. The Smith Control Scheme

The Smith control scheme was proposed in [1] to handle plants containing pure-time delays; i.e., plants having a transfer function of the form:

$$G(s) = G_R(s)e^{-s\tau} \quad (1)$$

where $G_R(s)$ is a rational transfer function, and τ denotes the time delay. Within the Smith control scheme, one first designs a compensator $K(s)$ which stabilizes the rational part $G_R(s)$ (Fig. 2(a)). Then an auxiliary loop is placed around the compensator $K(s)$ to ensure nominal stability of the irrational function $G(s)$ (Fig. 2(b)).

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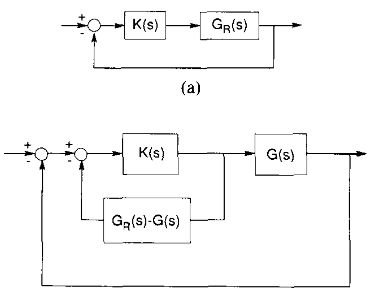

Fig. 3. Block diagram of the extension of the Smith control scheme showing: (a) Reduced loop, and (b) auxiliary loop.

We now present two multivariable extensions of the basic Smith scheme, each handling a system of a particular form.

A. First Multivariable Extension

Consider a multivariable system with an irrational $m \times m$ transfer function matrix $G(s)$ which represents a (linear) physical system (i.e., a proper contour can be found in the complex s-plane such that the Laplace transform of $G(s)$ provides a causal impulse response function matrix) and which can be written in the following special form:

$$G(s) = G_I(s) G_R(s) \quad (2)$$

where $G_R(s)$ is a rational, strictly proper $m \times m$ exponentially stable transfer matrix, and $G_I(s)$ is an $m \times m$ irrational transfer matrix containing no singularities in the right-half plane. Let $K(s)$ denote an $m \times m$ stable compensator designed to stabilize $G_R(s)$ (the closed-loop scheme involving $G_R(s)$ will be called in the sequel the "reduced loop"). Then the scheme of Fig. 3 is nominally stable.

The proof is as follows: The equivalent compensator $K_1(s)$ in the Smith scheme is

$$\begin{aligned} K_1(s) &= \{I + K(s)[G_R(s) - G(s)]\}^{-1} K(s) \\ &= [K^{-1}(s) + G_R(s) - G(s)]^{-1}. \end{aligned} \quad (3)$$

Hence the closed-loop transfer function matrix $G_{CLS}(s)$ for the Smith controller is

$$\begin{aligned} G_{CLS}(s) &= [I + G(s) K_1(s)]^{-1} G(s) K_1(s) \\ &= G(s) K(s) [I + G_R(s) K(s)]^{-1} \\ &= G_I(s) G_R(s) K(s) [I + G_R(s) K(s)]^{-1}. \end{aligned} \quad (4)$$

The reduced-loop system has the closed-loop transfer function matrix (Fig. 3):

$$G_{CLR}(s) = G_R(s) K(s) [I + G_R(s) K(s)]^{-1}. \quad (5)$$

By construction, the reduced loop is stable, hence the reduced-loop characteristic polynomial $\phi_R(s)$ contains no zeros in the closed right-half plane. Thus the closed-loop system function $\Phi(s)$ defined as [12]

$$\Phi(s) = \phi_R(s) \det [I + G_R(s) K(s)] \quad (6)$$

has the same right-half plane zeros as the polynomial of the reduced loop, as evidenced from (4), and given that $G_I(s)$ has no singularities in the right-half plane. This completes the proof. Our supposition and results parallel similar developments in [4] as far as nominal stability is concerned.

Since the Nyquist plot for $G_{CLS}(s)$ is essentially that of the reduced loop, one may infer that the system will have similar robustness properties to the reduced loop when considering variations in $G_R(s)$. In Section IV, we consider the robustness of the system to variations in $G_I(s)$.

B. Second Multivariable Extension

Next we consider the more general case of a multivariable system with $m \times m$ transfer function matrix $G(s)$, which is open-loop stable and which again may be irrational but cannot be written in the form given by (2). Again, we assume that a proper contour can be found in the complex s-plane, such that the Laplace inversion of $G(s)$ provides a causal impulse response function matrix.

Let $G_R(s)$ denote an $m \times m$ rational, exponentially stable, strictly proper transfer function matrix which is obtained by simplifying (in any arbitrary manner) $G(s)$. Then if the compensator $K(s)$ is designed for the open loop $G_R(s)$, the generalized Smith control scheme shown in Fig. 3 is nominally stable.

The proof is as follows: The closed-loop transfer function matrix for the reduced system $G_{CLR}(s)$ is given by (5), while we find that the closed-loop transfer function matrix for the Smith controller $G_{CLS}(s)$ is simply,

$$G_{CLS} = G(s) K(s) [I + G_R(s) K(s)]^{-1}. \quad (7)$$

Then following the same steps as in the previous case (i.e., by comparing the two closed-loop transfer functions and by virtue of the Nyquist criterion [13]), the stability of the first implies the stability of the second.

The requirement for open-loop stability is a basic restriction of the Smith controller as shown in [4] and [14]. The basic scheme can be modified to remove this requirement [14]. However, this will not be pursued here.

III. Design of $K(S)$ Using the LQG/LTR Methodology

In designing the compensator $K(s)$ for the reduced loop $G_R(s)$, we employ the LQG/LTR methodology to ensure sufficient robustness margins. A detailed account of the methodology can be found in [10], [11], and so only a brief description is given here. An optimal regulator and a Kalman filter are cascaded in a classical LQG configuration [15], but the regulator is parametrized with respect to the scalar weight of the control-penalty matrix, denoted as ρ. As ρ tends to zero, it is shown that the closed-loop transfer function tends pointwise to the Kalman filter transfer function, whose very good robustness properties are well known [16], [17]. These properties include:

1) 60° of phase margin (positive or negative) in each channel, separately or simultaneously.

2) Infinite upward gain margin and one-half reduction gain margin in each channel, separately or simultaneously.

3) The condition for this asymptotic result is that the open-loop plant contains no nonminimum phase zeros.

IV. Robustness Properties of the Robust Smith Controller

We will refer in the sequel to a "Robust Smith Controller" to denote a Smith control scheme whose compensator $K(s)$ has been designed based on the LQG/LTR methodology.

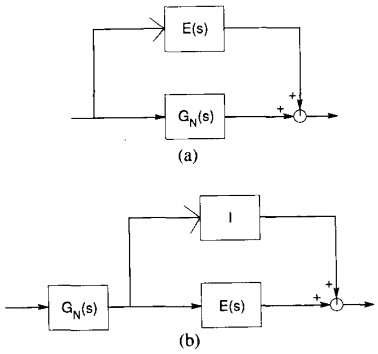

Fig. 4. Representation of the plant error: (a) Additive, and (b) multiplicative.

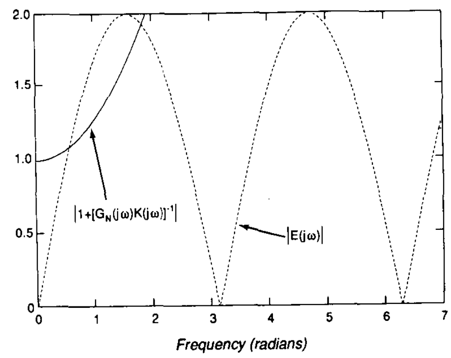

Fig. 5. Robustness test for a plant containing a pure time delay.

The nominal system in the Smith control scheme enjoys the same robustness properties as the reduced scheme, as shown above. Hence the closed-loop transfer function matrix has the robustness properties mentioned in the previous section, provided that the reduced (rational) transfer function used to design the compensator has no nonminimum phase zeros.

We consider a multivariable system with transfer function matrix $\boldsymbol{G}(s)$. Let $\boldsymbol{G}_N(s)$ denote the nominal value of the same transfer function which is subject to (unknown) variations. Then the design of the auxiliary loop in Fig. 3(b) is based on $\boldsymbol{G}_N(s)$, where the rational transfer function matrix $\boldsymbol{G}_R(s)$ is obtained as a reduction of $\boldsymbol{G}_N(s)$. In this case, the closed-loop transfer function matrix $\boldsymbol{G}_{\mathrm{CLS}}(s)$ becomes:

$$\boldsymbol{G}_{\mathrm{CLS}}(s) = \boldsymbol{G}(s)\boldsymbol{K}(s) \cdot \left\{ \boldsymbol{I} + \boldsymbol{G}_R(s)\boldsymbol{K}(s) + \left[\boldsymbol{G}(s) - \boldsymbol{G}_N(s)\right]\boldsymbol{K}(s)\right\}^{-1}. \quad (8)$$

We distinguish two cases: An additive variation and a multiplicative variation.

A. Additive Variation

If the variation in the plant is in the form of an additive error as defined by the matrix $\boldsymbol{E}$ in Fig. 4(a), then the stability-robustness test requires [11]:

$$\sigma_{\max}\left[\boldsymbol{E}(j\omega)\right] < \sigma_{\min}\left[\boldsymbol{G}_{\mathrm{CLS}}(j\omega)\right] \quad (9)$$

where $\sigma_{\max}[\boldsymbol{A}]$ and $\sigma_{\min}[\boldsymbol{A}]$ denote the maximum and minimum singular values of matrix $\boldsymbol{A}$, respectively. If we consider that the variation is in the form of an additive matrix $\boldsymbol{\Delta}(s)$, such that

$$\boldsymbol{G}(s) = \boldsymbol{G}_N(s) + \Delta(s) \quad (10)$$

then the robustness criterion takes the form:

$$\sigma_{\max}\left[\Delta(s)\boldsymbol{K}(s)\right] < \sigma_{\min}\left[\boldsymbol{I} + \boldsymbol{G}_R(s)\boldsymbol{K}(s)\right]. \quad (11)$$

B. Multiplicative Variation

If the variation in the plant is in the form of a multiplicative error as defined by the matrix $\boldsymbol{E}$ in Fig. 4(b), then the stability-robustness test is [11]

$$\sigma_{\max}\left[\boldsymbol{E}(j\omega)\right] < \sigma_{\min}\left[\boldsymbol{G}_{\mathrm{CLS}}^{-1}(j\omega)\right]. \quad (12)$$

If we consider the following variation:

$$\boldsymbol{G}(s) = \boldsymbol{G}_I(s)\boldsymbol{G}_R(s)$$
$$\boldsymbol{G}_N(s) = \boldsymbol{G}_{IN}(s)\boldsymbol{G}_R(s) \quad (13)$$

then the robustness criterion provides:

$$\sigma_{\max}\left[\boldsymbol{G}_I - \boldsymbol{G}_{IN}(s)\right] < \sigma_{\min}\left\{\boldsymbol{I} + \left[\boldsymbol{G}_R(s)\boldsymbol{K}(s)\right]^{-1}\right\}. \quad (14)$$

C. Application to a System with a Pure Time Delay

It is of interest to focus on a system which contains delays and consider the robustness of the Robust Smith Controller to errors in the time-delay constant.

We consider an open-loop system with the nominal transfer function matrix:

$$\boldsymbol{G}_N(s) = \boldsymbol{G}_R(s)e^{-s\tau_N} \quad (15)$$

where $\boldsymbol{G}_R(s)$ is a strictly proper, stable, rational transfer function that contains no nonminimum phase zeros. Let $\boldsymbol{K}(s)$ denote the LQG/LTR controller which stabilizes $\boldsymbol{G}_R(s)$. We consider now the Robust Smith Controller and in particular, a modeling error in the time-delay constant. Let τ denote the actual value of the time constant, and τ_N be the nominal value around which the system has been designed. The error can be cast as an output multiplicative error—i.e., if $\boldsymbol{G}(s)$ denotes the actual open-loop transfer function matrix, then

$$\boldsymbol{G}(s) = \boldsymbol{G}_N(s)e^{-s(\tau-\tau_N)}$$
$$= \left[\boldsymbol{I} + \boldsymbol{E}(s)\right]\boldsymbol{G}_N(s) \quad (16)$$

where

$$\boldsymbol{I} + \boldsymbol{E}(s) = \boldsymbol{I}e^{-s(\tau-\tau_N)}. \quad (17)$$

Given (16) and based on the stability-robustness test of (12), we find:

$$\left|1 - e^{-j\omega(\tau-\tau_N)}\right| = \sqrt{2 - 2\cos\left[\omega(\tau - \tau_N)\right]} < 1. \quad (18)$$

Equation (18) restricts the bandwidth of the system, as shown in Fig. 5, providing a rough estimate of the cut-off frequency ω_c:

$$\omega_c < \frac{\pi}{\left|2(\tau - \tau_N)\right|}. \quad (19)$$

D. Application to a Single Input-Single Output System with Nonminimum Phase Zeros

We consider an open-loop, single input-single output (SISO) system with the following transfer function:

$$G(s) = G_1(s)(s - a) \quad (20)$$

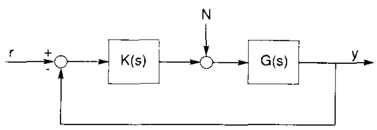

Fig. 6. Disturbances at plant input.

where a is positive, and $G_1(s)$ is a strictly proper, stable, rational transfer function that contains no nonminimum phase zeros. A nonminimum phase zero poses intrinsic difficulties for control, as outlined in some detail in [18]. The essence of these difficulties is the noninvertibility of the plant, hence making a close connection between a nonminimum phase zero and a time delay. In fact, if we set:

$$G(s) = G_2(s)\frac{s-a}{s+a} \tag{21}$$

where

$$G_2(s) = G_1(s)(s+a) \tag{22}$$

then the last term on the right-hand side of (21) is the first-order Pade approximation of a delay. Hence the Smith control scheme can be applied directly, substituting the ratio $(s-a)/(s+a)$ for the delay and using $G_2(s)$ as the reduced plant transfer function. Thus, robustness of the system with a nonminimum phase zero is achieved.

V. Disturbance Rejection

We consider the SISO case and study rejection of disturbances $N(t)$ at the input (Fig. 6). In a classical control scheme (i.e., when $G(s)$ is rational and $K_1(s) = K(s)$), the output $y(s)$ is given as

$$y(s) = \frac{G(s)}{1+G(s)K(s)}N(s) + \frac{G(s)K(s)}{1+G(s)K(s)}r(s). \tag{23}$$

For good disturbance rejection it is sufficient to have $|N(s)| \ll |K(s)|$. For the Smith scheme described by (1), we find:

$$\begin{aligned} y(s) &= \frac{G(s)}{1+G(s)K_1(s)}N(s) + \frac{G(s)K_1(s)}{1+G(s)K_1(s)}r(s) \\ &= \frac{1+K(s)G_R(s)[1-e^{-s\tau}]}{1+K(s)G_R(s)}G_R(s)e^{-s\tau}N(s) \\ &\quad + \frac{G(s)K_1(s)}{1+G(s)K_1(s)}r(s). \end{aligned} \tag{24}$$

We concentrate on the response due to the disturbances $N(s)$ by setting $r(s) = 0$ in (24). Since $K(s)$ is based on $G_R(s)$, we have $K(s)G_R(s) \gg 1$, hence:

$$\begin{aligned} y_N(s) &= G_R(s)e^{-s\tau}N(s), \quad \text{if } |s\tau| = O(1) \\ y_N(s) &= \frac{1}{K(s)}e^{-s\tau}N(s), \quad \text{if } |s\tau| \ll 1. \end{aligned} \tag{25}$$

We conclude from (25) that disturbance rejection is achieved over the low-frequency range, defined by the condition that $\omega\tau \ll 1$, such that the magnitude of $K(s)G_R(s)$ is not allowed to become arbitrarily large, since:

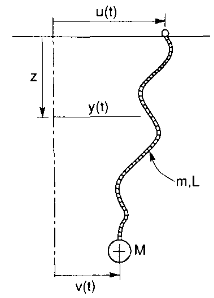

Fig. 7. Tether-mass positioning system (in air).

$$|K(s)G_R(s)| < \frac{1}{|1-e^{-s\tau}|} = \frac{1}{\sqrt{2[1-\cos(\omega\tau)]}}. \tag{26}$$

Under these conditions,

$$y_N(s) = e^{-s\tau}\frac{N(s)}{K(s)} \tag{27}$$

and hence if $|K(s)| \gg |N(s)|$, then $|y(s)| \ll 1$.

VI. Good Command Following

Continuing our consideration of the SISO plant and in view of (24), we find that the requirement for good command following is that $|G(s)K(s)| \gg 1$ over the frequency range of interest. In this respect, the Smith scheme has the same properties as classical feedback systems and we need not pursue the subject any further.

VII. Two Examples of the Robust Smith Controller

The first example considers the SISO system with open-loop transfer function:

$$G(s) = \frac{e^{-s\tau}}{(s+1)^2}. \tag{28}$$

We first apply LQG/LTR to the rational part of the transfer function, $G_R(s) = 1/(s+1)^2$, and recover, in the limit, the target-loop transfer function. Then the robustness condition (18) provides a direct assessment of robustness in terms of the recovered loop parameters [11] and the delay mismatch.

For the second example we consider a more complex system which in fact resembles the actual system under study, the remote positioning of a mass M through a vertical tether of length L, mass per unit length m, and (presumed constant) tension T (Fig. 7). The most important difference from the actual system (considered in the next section) is the absence of fluid drag. The transfer function $G(s)$ between the imposed motion at the top $u(t)$ and the response of the mass $v(t)$ is

$$G(s) = \frac{1}{\left[\frac{csM}{T}\sinh\left(\frac{sL}{c}\right) + \cosh\left(\frac{sL}{c}\right)\right]} \tag{29}$$

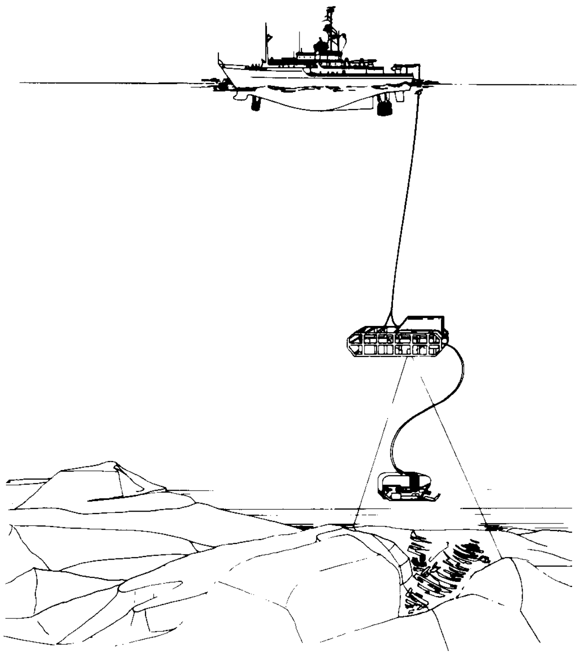

Fig. 8. Principal system under study, consisting of a dynamically positioned surface ship, a long tether, a passive survey vehicle, and a remotely operated vehicle connected to the survey vehicle through a second tether.

where

$$c = \sqrt{\frac{T}{m}}.$$

This expression can be nondimensionalized to give:

$$G(\hat{s}) = \frac{1}{\beta\hat{s}\sinh(\alpha\hat{s}) + \cosh(\alpha\hat{s})} \tag{30}$$

where

$$\hat{s} = \frac{s}{\sqrt{\frac{T}{(M + \frac{1}{2}mL)L}}} \tag{31}$$

and

$$\alpha = \frac{1}{\sqrt{\mu + \frac{1}{2}}}, \qquad \beta = \alpha\mu, \qquad \mu = \frac{M}{mL}. \tag{32}$$

A rational approximation $G_R(s)$ is obtained for low frequencies (representing an equivalent pendulum) in the form:

$$G_R(\hat{s}) = \frac{1}{\hat{s}^2 + 1}. \tag{33}$$

We may apply LQG/LTR to (33) and recover the target loop, thus guaranteeing for the nominal loop the good robustness properties of the Kalman filter loop. The robustness tests express directly the robustness to parameter mismatch, such as the tether properties or the mass M.

VIII. Application to Tethered Underwater Vehicles

The physical system under study is seen in Fig. 8. Here, a surface ship is shown positioning an underwater vehicle through a long tether. The vehicle may be searching the ocean floor or mapping the topography of the bottom, or it may be the platform for a smaller vehicle equipped with its own thrusters.

For bottom search, the tether has a length that is slightly larger than the water depth. Since 85% of the ocean is deeper than 2500 m, tethers are usually very long, having slow dynamics with time constants in the range of 1 to 5 min. Manually controlling the vehicle is almost impossible, because human operators cannot control systems with such long time constants. As we have shown, automatic control requires special attention when handling systems with time delays, making this problem different from the vehicle control problem studied, for example, in [19].

The experiments reported in [20]–[23] established the basic properties of the open-loop system (Fig. 8). The underwater vehicle is to be controlled through dynamic positioning (DP) of the surface vessel. The DP system uses the surface ship's thrusters to provide the control force and hydrophones and submerged pingers to position itself. The DP system may be modified to utilize the measured position of the underwater vehicle, so as to achieve the desired goal directly.

The dynamics of the tether and attached vehicle have been modeled by a set of nonlinear partial differential equations as described in [24], and the predictions have been confirmed by direct comparison with the full-scale data. By comparing the results of the nonlinear model to parametric models, the following approximation was derived for the transfer function between imposed ship motion and vehicle response:

$$G_R(s) = \frac{ce^{-s\tau}}{ms^2 + bs + c} \tag{34}$$

where $m = 1$, $b = 1.1 \times 10^{-4}$, $c = 2.58 \times 10^{-2}$, and $\tau = 40$ s. The model is valid for a cable 2500-m long and a vehicle weighing 17 000 N in air.

Subsequently, we applied LQG/LTR to the function $G_R(s)$ and used the extended Smith scheme to obtain a controller [25]. Fig. 9 shows results from one simulation, demonstrating command following. For the actual system we employed the nonlinear model. The desired path is shown by the dotted line (a rising ramp, a constant value, and a declining ramp returning the vehicle to its original position). The dashed line represents the actual vehicle position. The ship-commanded position (i.e., the

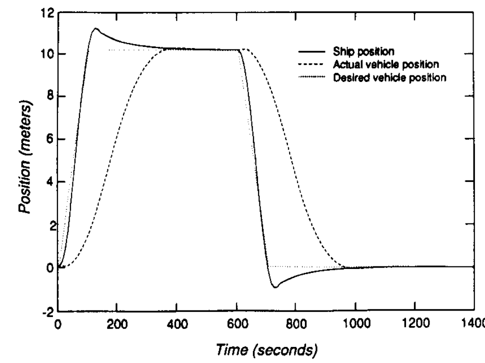

Fig. 9. Command following of a submerged-survey vehicle that is being positioned through the commanded movements of a surface ship. The desired vehicle position consists of a rising ramp, a constant value, and then a declining ramp. "Actual" vehicle position was calculated using the nonlinear numerical model of [24] with the ship position as input.

control output, shown by the solid line) has the features of a strong lead controller, characteristic of the Smith scheme. The initial delay is intrinsic to the system and causes the initial deviation from the desired path (which is unavoidable). Good overall performance is achieved, given the crudeness of the approximations used in deriving (34).

IX. Conclusions

A control scheme has been presented, based on extensions of the Smith controller and the LQG/LTR methodology, to handle systems with time delays, or more generally with irrational transfer functions. The methodology is applicable to underwater vehicles which are controlled through an acoustic link or tethered vehicles which are positioned through the movements of a surface-support ship. An example of the method is presented for the tethered underwater vehicle ARGO, whose dynamics involve long delays of the order of several minutes.

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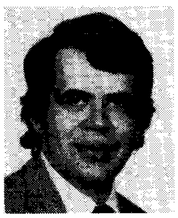

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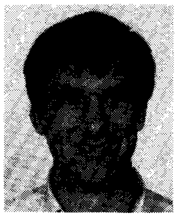

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