A NOVEL SMITH PREDICTOR SCHEME APPLIED TO A FULLY ACTUATED INVERTED PENDULUM

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Abstract: In this paper we show the effectiveness of a novel control scheme for dead-time systems recently proposed in (Zaccarian and Nešić, 2006 American Control Conference). In that paper, the prediction problem is formally stated and shown to be achievable for any type of dead-time system, as long as it is possible to determine a stabilizing control law. We propose here the employment of an LMI-based control strategy for this stabilization task and show the advantages of the novel modified Smith predictor scheme on a MIMO example. In particular, satisfactory simulation results are given both for the linearized model and for the nonlinear model of an inverted pendulum subject to disturbances.

1. INTRODUCTION

The first non-trivial solution to stabilization of dead-time processes was given by O.J.Smith in (Smith, 1957) who presented a controller-predictor structure in which the controller is designed for the delay-free plant. The arising closed-loop performance is then enforced on the actual plant with time-delay via the action of a peculiar filter (the Smith predictor) which has a model-based structure. In general, the classical Smith predictor has some important limitations, the main one being that it can only be applied to open-loop asymptotically stable plants. Already in the 1980s generalizations of the classical Smith predictor scheme were proposed (see, e.g., (Watanabe and Ito, 1981)). Useful extensions of the original Smith predictor scheme were given in (Astrom *et al.*, 1994) to extend its applicability to plants with integrating action, as well as in subsequent works where these results were also extended to open-loop unstable plants (a nice summary and overview of these advances is given in (Palmor, 1996)). Despite the large literature on stabilization of time-delay systems, in recent years the Smith predictor has been a preferred technique for the design of high performance control schemes for dead-time processes (see the references in (Zaccarian and Nešić, 2006) for some recent works where modified Smith predictors have been successfully employed in many relevant case studies).

In the recent paper (Zaccarian and Nešić, 2006) we have proposed a framework for the enhancement of the classical Smith predictor with the goal of making it applicable to generic (also exponentially unstable) MIMO plants with input delay. The proposed framework has the advantage of not being specific to a special structure of the plant dynamics but doesn't provide a fully constructive solution to the problem as it reduces the Smith

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prediction problem to the design of a stabilizer for the dead-time plant which acts like a key feedback loop within the enhanced compensation scheme (this loop has zero gain in the classical Smith predictor). In this paper we make a step forward with respect to the technique proposed in (Zaccarian and Nešić, 2006) because we propose a dynamic selection of the stabilizer which is able to induce very desirable results even on MIMO exponentially unstable plants. The resulting performance can be appreciated on a relevant case study corresponding to the linearized (and nonlinear) dynamics of a fully actuated inverted pendulum around the "up" position.

The paper is organized as follows. In Section 2 we give the problem data. In Section 3 we recall the main result from (Zaccarian and Nešić, 2006) and propose the novel selection of the extra stabilizing feedback. Finally, in Section 4 we use a nonlinear and linearized model of the inverted pendulum about the "up" position and show the great advantages of the scheme when the control input is delayed.

2. PROBLEM DATA

Consider the following MIMO linear plant having a uniform delay τ at its control input:

$$\mathcal{P}\begin{cases}\dot{x}(t)=Ax(t)+B_u u(t-\tau)+B_d d(t)+\psi_x(t)\\ y(t)=x(t)+D_{dy}d(t)+\psi_y(t)\\ z(t)=C_z x(t)+D_{uz}u(t-\tau)+D_{dz}d(t)+\psi_z(t).\end{cases} \quad (1)$$

In (1), $x \in \mathbb{R}^{n_p}$ is the plant state, $y \in \mathbb{R}^{n_p}$ is the measured output, $z \in \mathbb{R}^{n_z}$ is the performance output, $u \in \mathbb{R}^{n_u}$ is the control input and $d \in \mathbb{R}^{n_d}$ is a disturbance input. The three extra signals ψ_x, ψ_y, ψ_z can be stacked in a single vector Ψ representing the output of the following linear system resembling plant uncertainties and unmodeled linear dynamics:

$$\Psi(t)=\begin{bmatrix}\psi_x(t)\\ \psi_y(t)\\ \psi_z(t)\end{bmatrix}=\Delta(s)\begin{bmatrix}x(t)\\ u(t)\\ d(t)\end{bmatrix} \quad (2)$$

which may be infinite dimensional (it may have internal delays). We will need the following assumption to hold for the system (1), (2).

Assumption 1. The pair (C_z, A) is detectable. The linear system (2) is an exponentially stable linear retarded delay-differential system with finite $\mathcal{L}_2$ gain equal to γ_Δ.

Remark 1. In general, the linear system (2) can be used to represent several aspects of the plant which don't appear in the model (1). In this paper, we will use it to represent the dynamics of an observer which estimates the state of the plant. In particular, assume that full state measurement is not available for the plant (1). Then, assuming for simplicity that all the parameters in (1) are perfectly known (in the opposite case, extra terms would appear in (2)), the following selection for (2) represents the presence of an observer from an output $y_m(t) = C_{ym}x(t)+D_{ym}u(t-\tau)+D_{dym}d(t)$ with observation gain L:

$$\dot{x}_\delta(t) = (A-LC)x_\delta(t) + (B_u - LD_{dym})d(t)$$
$$\psi_x(t) = 0, \quad \psi_y(t) = -x_\delta(t), \quad \psi_z(t) = 0$$

where x_δ is the state of the system (2) and represents the observation error. Note that as long as the observer is an asymptotic observer (namely, $A - LC$ is Hurwitz), the dynamics (2) is exponentially stable, as required in Assumption 1. Moreover, by appropriately selection L, the gain from d to ψ_y can be made small. ∘

Consider the plant (1) and assume that a linear controller has been designed [4] to guarantee desirable stability and performance specifications on its *undelayed closed-loop interconnection* with the nominal undelayed plant (see Figure 1), namely

$$\mathcal{P}_0\begin{cases}\dot{x}_u(t) = Ax_u(t)+B_u u_u(t)+v_1(t)\\ y_u(t) = x_u(t)+v_2(t)\\ z_u(t) = C_z x_u(t)+D_{uz}u_u(t),\end{cases} \quad (3a)$$

$$\mathcal{C}\begin{cases}\dot{x}_c(t) = A_c x_c(t)+B_c u_c(t)+B_r r(t)\\ u(t) = C_c x_c(t) D_c u_c(t)+D_r r(t),\end{cases} \quad (3b)$$

$$u_u(t) = u(t), \qquad u_c(t) = y_u(t), \quad (3c)$$

where v_1 and v_2 are suitable signals to be specified later. We will assume that the following assumption holds for the undelayed nominal closed-loop system.

Assumption 2. The *undelayed nominal closed-loop system* (3a), (3b), (3c) (with $v_1 \equiv v_2 \equiv 0$) is globally exponentially stable.

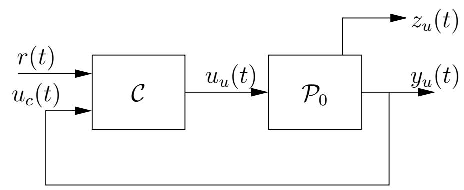

Fig. 1. The undelayed nominal closed-loop system.

The main contribution of (Zaccarian and Nešić, 2006) was to provide a framework for the recovery of the linear performance characterizing

[4] In general, the controller (3b) may be nonlinear as long as it guarantees suitable $\mathcal{L}_2$ and incremental $\mathcal{L}_2$ stability conditions (see (Zaccarian and Nešić, 2006) for details). Since we use a linear controller in this paper, we decided to simplify the discussion and concentrate only on the linear case.

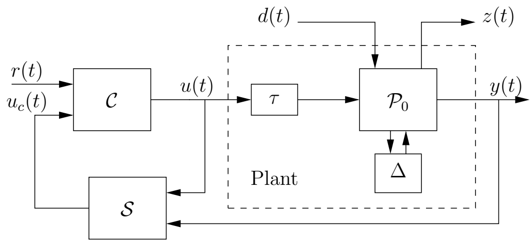

Fig. 2. The compensated closed-loop system.

the undelayed closed-loop also on the dead-time plant. To this aim, it was shown in (Zaccarian and Nešić, 2006) that while a standard Smith predictor scheme could be used whenever the plant (1) is exponentially stable, an extra stabilizing action is necessary for the case when this exponential stability condition is not satisfied. In particular, the problem addressed and solved in (Zaccarian and Nešić, 2006) was to design an enhanced Smith predictor $\mathcal{S}$ as in Figure 2 such that the following property is satisfied by the *compensated closed-loop.*

Definition 1. (Zaccarian and Nešić, 2006) The delay compensation system $\mathcal{S}$ is said to solve the *nominal prediction problem* if under the assumption that $d(\cdot) \equiv 0$ and $\Psi \equiv 0$, for any selection of the reference signal $r(\cdot)$, and zero initial conditions, the performance output responses of the undelayed and of the compensated closed-loops satisfy $z(t) = z_u(t-\tau)$ for all $t \geq \tau$.

The delay compensation system $\mathcal{S}$ is said to solve the *robust prediction problem* if

(1) it solves the nominal prediction problem
(2) for a sufficiently small gain $\gamma_\Delta > 0$ of the unmodeled dynamics (2) and under Assumption 1, there exists $\gamma > 0$ such that the performance output responses of the undelayed and of the compensated closed-loops satisfy

$$\|z(\cdot)-z_u(\cdot-\tau)\|_2 \leq \gamma(\|d(\cdot)\|_2+\gamma_\Delta\|r(\cdot)\|_2) \quad (4)$$

3. THE ENHANCED SMITH PREDICTOR

We recall in this section the solution proposed in (Zaccarian and Nešić, 2006) to the nominal and robust prediction problems introduced in the previous section. In particular, we rewrite all the conditions of the theorem assuming that the state of the plant is completely available for measurement. The solution proposed in (Zaccarian and Nešić, 2006) generalizes the classical Smith predictor scheme of (Smith, 1957) and corresponds to the insertion of the following filter:

$$\mathcal{S}\begin{cases}\dot{x}_s(t) = Ax_s(t) + B_u u(t) + v_1(t)\\ u_c(t) = x_s(t) + v_2(t)\\ \tilde{x}(t) = y(t) - x_s(t-\tau),\end{cases} \quad (5)$$

where the two signals $v_1(t)$ and $v_2(t)$ represent the "enhancement" and are feedback signals from the prediction error $\tilde{x}$ (so that, among other things, $\tilde{x}(\cdot) \equiv 0$ implies $v_1(\cdot) \equiv 0$ and $v_2(\cdot) \equiv 0$). We recall that the classical Smith predictor corresponds to a specific selection of these signals, namely $v_1(t) = 0$ and $v_2(t) = \tilde{x}(t)$.

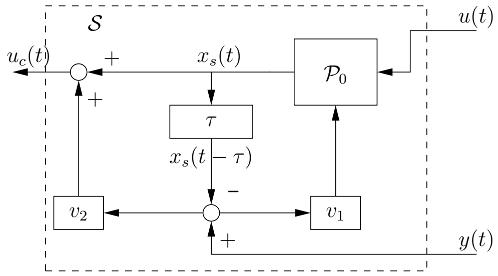

Fig. 3. The enhanced Smith predictor.

The enhanced Smith predictor (5) represents a useful generalization of the classical Smith predictor because as long as v_1 and v_2 are zero when $\tilde{x}$ is zero, the nominal prediction property of Definition 1 will always be satisfied regardless of the selection of these two signals. On the other hand, all the possible selections of v_1 and v_2 that arise from a (static or dynamic, linear or nonlinear) feedback loop from the signal $\tilde{x}$, parametrize a family of enhanced Smith predictors that, as shown in the following sections, is large enough to allow to solve the robust prediction problem of Definition 1 for non exponentially stable plants (thus reaching beyond the potentials of the classical Smith predictor). Then, the solution to the (nominal and robust) prediction problem is reduced to the solution of a simpler delayed stabilization problem via the two signals v_1 and v_2.

In (Zaccarian and Nešić, 2006) we didn't provide an effective selection of the signals v_1 and v_2, as a matter of fact, we only focused on the most trivial selection corresponding to:

$$\begin{aligned} v_1(t) &= K_s\tilde{x}(t)\\ v_2(t) &= \tilde{x}(t),\end{aligned} \quad (6)$$

where K_s was determined by solving a very simple linear matrix inequality (LMI) guaranteeing finite-gain $\mathcal{L}_2$ stability for any value of the delay τ (a delay-independent condition). It is well known that delay-independent conditions are very conservative and, indeed, the underlying LMIs are rarely feasible with non Hurwitz plants (moreover, in those cases where a solution is found, it typically leads to poor performance). We propose here a different approach aimed at high performance compensation for MIMO exponentially unstable plants and we rely for this on delay-dependent conditions for a dynamic selection of $v_1(t)$. As far as $v_2(t)$ is concerned, as extensively discussed in (Zaccarian and Nešić, 2006, Remark 4), it is quite important that it is selected as in (6) because the arising closed-loop system will preserve a possible asymptotic rejection of constant disturbances acting on the plant. This feature is commonly implemented in control systems and the example treated in the next section characterizes one of those cases.

In this paper we propose the following selection of v_1 which has shown very good performance on several examples and guarantees feasibility for sufficiently small τ on any (possibly exponentially unstable) plant.

Theorem 1. Consider a linear delayed plant (1) and a controller (3b), Assume that Assumptions 1 and 2 hold. Given any Hurwitz matrix $A_a \in \mathbb{R}^{n_u \times n_u}$, consider the following dynamic selection of the signal $v_1(t)$:

$$\begin{aligned} \dot{x}_a(t) &= A_a x_a(t) + K_a \begin{bmatrix} x_a(t) \\ \tilde{x}(t) \end{bmatrix}, \\ v_1(t) &= x_a(t), \end{aligned} \qquad (7)$$

where, given the optimal solution U_0^*, η^*, X^*, Y^* to the following generalized eigenvalue problem in the variables $\Gamma = \Gamma^T > 0$, $U_0 = U_0^T > 0$, $X = X^T > 0$, Y and $\eta > 0$:

$$\min_{U_0, X, Y, \eta} \eta, \quad \text{subject to} \qquad (8)$$

$$\left[\begin{array}{c|c} U_0 & \begin{bmatrix} 0 & A_a \\ 0 & 0 \end{bmatrix} X + \begin{bmatrix} 0 \\ I \end{bmatrix} Y \\ \hline \star & -U_0 \end{array}\right] < \left[\begin{array}{c|c} \Gamma & 0 \\ \hline 0 & 0 \end{array}\right],$$

$$\Gamma < \eta \mathrm{He}\left(- \begin{bmatrix} A & I \\ 0 & A_a \end{bmatrix} X - \begin{bmatrix} 0 \\ I \end{bmatrix} Y \right),$$

the matrix K_a is selected as $K_a = Y^*(X^*)^{-1}$. (In (8), "$\star$" denotes the transpose of its symmetric entry and $\mathrm{He}(M) := M + M^T$.) Then, the enhanced Smith predictor (5), (7) solves the (nominal and) robust prediction problem of Definition 1 for all $\tau \leq 1/\eta^*$.

Remark 2. Note that the selection strategy for v_1 proposed in Theorem 1 corresponds to transforming a control problem for a plant with delayed input into a control problem for a plant with delayed state. This fact is obtained by augmenting the plant with extra states whose derivative will be imposed by way of an artificial external input. This trick is quite well known in the time-delay literature and has been used in several papers (see, e.g., (Pandolfi, 1995; Germani *et al.*, 1995)). ∘

4. A MIMO EXAMPLE: THE INVERTED PENDULUM

In this section we apply the enhanced Smith predictor design methodology illustrated in Section 3 to the nonlinear model of a fully actuated inverted pendulum. The reason why we consider full actuation (namely both a motor exerting a force on the cart and a motor exerting a torque on the pendulum hinge) is that we would like to illustrate the advantages of the proposed Smith prediction scheme when trying to recover (in a delayed way) the performance induced by a decoupling controller. In general, obtaining a decoupling controller for a MIMO dead-time system is a hard task to accomplish. Moreover, if the system under consideration is exponentially unstable (such as the linearized dynamics of the inverted pendulum), this task becomes quite hard with the existing construction schemes. We show here how the enhanced Smith predictor scheme provides a simple to design and simple to implement solution to this problem. Moreover we show that the arising solution is quite robust toward the model nonlinearities and rejects quite well external disturbances and unmodeled observer dynamics.

4.1 Nonlinear and linearized models of the inverted pendulum

Here the model of the inverted pendulum Laboratory Experiment PS600, by AMIRA, is considered (AMIRA, 1996). To allow experimentation of extreme control law inducing decoupled performance, we assume that an extra motor is present on the experimental system, which exerts a torque on the pendulum hinge, so that the arising structure is fully actuated.

The linearized model around the equilibrium point $x_e = [0\ 0\ 0\ 0]^T$ corresponding to the "up" position of the pendulum is

$$\dot{x}(t) = Ax(t) + Bu(t), \qquad (9a)$$

with the following selection for the matrices $[A|B]$:

$$\left[\begin{array}{cccc|cc} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & -2.47 & -0.76 & 6.8e-4 & 0.247 & -0.475 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 4.75 & 20.3 & -0.0185 & -0.475 & 12.77 \end{array}\right] \qquad (9b)$$

where the system matrix A has four real eigenvalues in $[4.44\ 0\ -2.23\ -4.7]$, namely it is exponentially unstable with a dominant pole around 4.

4.2 Design of the decoupling controller

For the linearized system (9) it is possible to design a decoupling controller from a reference input $r(t) = [r_s(t)\ r_\phi(t)]^T$ to the position and angular outputs of the system $z(t) = \left[\begin{smallmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{smallmatrix}\right] x(t)$ (we adopt here the method in (Chen, 1984)). The decoupling controller has been designed as represented in the block diagram of Figure 4 which represents the undelayed closed-loop.

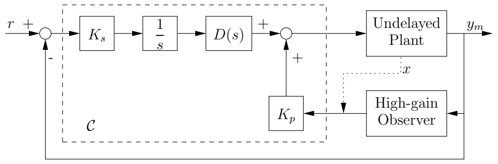

Fig. 4. The undelayed closed-loop between the plant and the decoupling controller.

In Figure 4 the structure of the controller corresponds to the a pre-stabilizing action via state feedback (by way of the block K_p) followed by a dynamic decoupler $D(s)$ which corresponds to a right inverse matrix for the process transfer matrix. Then, the forward control path (which has been made diagonal by the decoupler action) is augmented with an internal model of a constant reference (namely, an integrator) on each channel, so that constant references are asymptotically tracked and constant disturbances at the plant input (or output) are asymptotically rejected. Finally, the system is stabilized by way of the diagonal static stabilizing gain matrix K_s.

To resemble an actual implementation of the decoupling controller, we assume that the state of the system is not available for measurement but only the output $y_m(t) = [s(t)\ \ \phi(t)]^T$ is available and design a high-gain observer following the well-known technique widely used in the velocity estimation of mechanical systems (see, e.g., the pioneering paper (Nicosia *et al.*, 1990)).

4.3 Enhanced Smith predictor design and simulation results

We design here an enhanced Smith predictor for the control system in Figure 4 so that the augmented controller can tolerate a delay at the plant input. To this aim, we apply the construction of Theorem 1 and select the matrix A_a in (7) as $A_a = -\mathrm{diag}(0.1, 0.2, 0.3, 0.4)$ (note that this selection is not crucial at all, since the actual dynamics of the filter will be determined by the selection of K_a in the optimization (8). The selection of K_a is carried out by solving the optimization problem (8). To improve the numerical robustness of the optimizer, we add the following extra constraint to the optimization problem:

$$\begin{bmatrix} m_k I & Y \\ Y^T & m_k X \end{bmatrix} > 0, \quad X > I$$

which by Schur complement (conservatively) guarantees the constraint $K_a^T K_a < m_k^2 I$, thus keeping the entries of the matrix K_a limited. For our computation we have selected $m_k = 10^7$. The arising optimal gain is

$$K_a = \begin{bmatrix} -0.6993 & -0.20793 & 0.032351 & -0.0012797 \\ 2.3685 & -5.703 & -26.472 & -14.752 \\ 17.767 & -36.673 & -171.75 & -95.493 \\ 3.9785 & -8.1996 & -38.508 & -21.333 \\ -1.1682 & -0.27185 & 0.041338 & 0.0026028 \\ 0.37212 & -1.6539 & -5.8757 & -3.2881 \\ 3.9591 & -8.1344 & -38.424 & -21.221 \\ 0.87982 & -1.8452 & -8.56 & -4.8682 \end{bmatrix}^T$$

corresponding to an optimal value of $\eta^* = 4.97$. This means that the compensation system is guaranteed to tolerate an input delay of the process up to a maximum of $\tau_M = 1/\eta^* = 0.201\ s$.

We report next on the simulation results using the decoupling controller synthesized in Section 4.2 both on the plant with state measurement and on the plant without state measurement and augmented with the high-gain observer (which should be regarded as unmodeled dynamics resembled by equation (2)). We fix the input time delay to the value $\tau = 0.15$ which is below the value for which closed-loop stability is guaranteed by Theorem 1.

In each set of simulations we represent three curves: the first curve corresponds to the linear delayed response $z_u(\cdot)$ which is reported as a thin solid line in the time histories. This performance output corresponds to the ideal response to be recovered by the enhanced Smith predictor and corresponds to the ideal case where the time delay is pulled out from the feedback loop and inserted at the performance output of the plant. This response is of course not achievable on the actual dead-time plant because it supposes that the plant has no input delay. The second curve that we report using dotted lines is the response obtained by the mere interconnection of the decoupling controller to the dead-time plant without any extra compensating action. This response is always unacceptable and never converging. Finally, the third response that we report using bold solid line is the response obtained by the compensated system with dead-time and enhanced Smith prediction. This response aims at recovering the thin solid undelayed response. We don't report here on the simulations arising from the use of a classical Smith predictor because they all are exponentially diverging. As it is well known, when applied to exponentially unstable plants, the classical Smith predictor makes certain unstable modes unobservable, therefore always leading to non converging responses.

Figure 5 reports on a first set of simulations where we only consider the linear dynamics (9). The disturbance input is set to zero and full state measurement is assumed from the plant (namely, no observer is used for the plant state x). The following reference signal is selected:

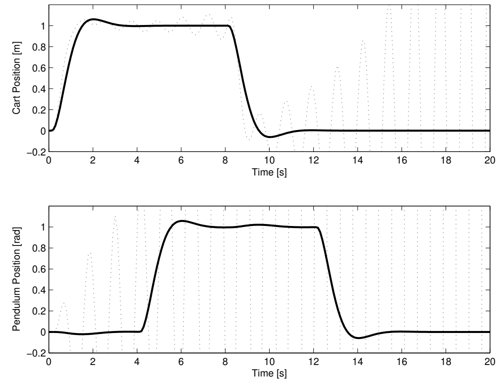

Fig. 5. Full state measurement and no dist.

$$\begin{aligned} r_s(t) &= \begin{cases} 1\ m, & \text{if } t \in [0, 8]\ s, \\ 0\ m, & \text{otherwise} \end{cases} \\ r_\phi(t) &= \begin{cases} 1\ rad, & \text{if } t \in [4, 12]\ s, \\ 0\ rad, & \text{otherwise} \end{cases} \end{aligned} \tag{10}$$

From the simulation it is evident that the enhanced Smith predictor fully recovers the undelayed performance. Note that the closed-loop without compensation already loses the stability properties.

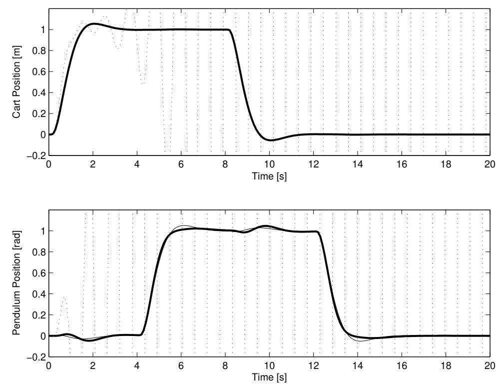

Fig. 6. High gain observer and no disturbances.

In the next Figure 6, we simulate the same exact scenario, assuming that full state measurement is not available to the controller, so that the high-gain observer is inserted at the plant output z (see Figure 4). The arising responses show a slight performance degradation both of the undelayed closed-loop and of the compensated closed-loop. The closed-loop without compensation becomes exponentially unstable.

We consider then in Figure 7 the action of a disturbance d acting at the same input as the control input. This disturbance resembles the presence of uncertainties in the power amplifiers driving the actuators and is selected as a constant offset of 0.1 (N or Nm) plus a band limited white noise with sample time 0.001 and noise power 0.00001 acting from time $t = 0$. The simulation is carried out on the linearized model (9) without full state measurement. As expected, the closed-loop performance further degrades but closed-loop stability of the compensated system is preserved. Finally, to illustrate the extreme robustness of the compensation scheme, in Figure 8 we test the control system on the full nonlinear model by keeping the same reference signal (10) which reaches far beyond the equilibrium point about which the linearization is carried out. A severe performance degradation is now experienced but closed-loop stability is still preserved. A degradation, especially in the pendulum position is to be expected due to the mismatch between the linearized and the nonlinear model when the pendulum angle is equal to 1 rad. Note that the response without compensation cannot be completed in this case due to excessively high values of the simulated response.

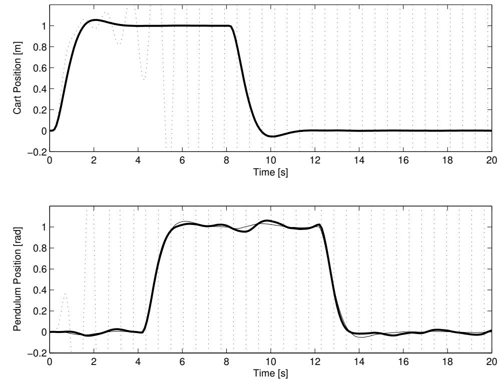

Fig. 7. High gain observer and step + white noise disturbances.

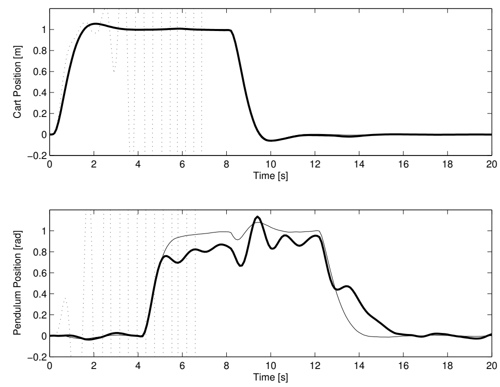

Fig. 8. Full nonlinear model.

5. CONCLUSIONS

In this paper we revisited a novel enhanced Smith predictor framework proposed in the recent paper (Zaccarian and Nešić, 2006 ACC). Within this framework, we proposed a compensation law which is able to induced delayed linear performance on generic exponentially unstable dead-time plants via the solution of delay-dependent Linear Matrix Inequality. A relevant simulation study has been carried out using decoupling controller on the linearized and nonlinear models of an inverted pendulum. The simulation results show extreme performance and robustness of the compensation scheme.

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