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Fast Output Sampling Feedback with Two Delayed Inputs for MIMO System

Arvind Pande
Amrutvahini College of Engineering
Sangamner-422608,
Maharashtra, India.
E-mail: arvindpandeengg@gmail.com.

Ravindra Munje
K. K. Wagh Institute of Engineering
Education and Research, Nashik-422003,
Maharashtra, India.
E-mail: ravimunje@yahoo.co.in

***Abstract*—In modified fast output sampling (FOS) feedback approach system states are estimated from the observations of previous outputs and an input. In this paper, a FOS scheme utilizing feedback of past outputs and two past inputs is proposed for multi-input multi-output (MIMO) system. It is shown that the addition of one more past input in the feedback results in improvement in the closed-loop system performance. The devised technique is examined for linear and nonlinear MIMO systems. For comparison purpose simulation results are generated using both modified FOS and proposed methods and it is observed that, the performance of suggested control technique is superior to former.**

Keywords: Inverted Pendulum, FOS, Multirate Output Feedback, MATLAB-Simulink.

I. Introduction

Multirate Output Feedback (MROF) is a control approach in which rather than feeding system output continuously, it is fed in intervals [1]. In MROF, the system input and output are sampled at different rates. One of the types of MROF is Fast Output Sampling (FOS) feedback [2], in which the system output is sampled at the faster rate than the control input. In FOS, the control signal is constrained to be a linear function of multirate output observation of the output signal. The control signal is kept constant over one discretizing interval and altered only at the input sampling intervals. Whereas in modified FOS, one previous control input along with past system outputs are used to calculate the present control signal. In this procedure, the invertibility constraint on state feedback gain matrix is eliminated [3], [4]. As an extension to this, a method is recommended in [5], which uses feedback of two consecutive previous inputs and past outputs to compute control input. However, the presented design procedure is not applicable for multi-input multi-output (MIMO) system.

In this paper, the technique of [5] is generalized for the multivariable system with comprehensive mathematical description. Moreover, the software implementation of the control algorithms (modified FOS and proposed FOS) are discussed with exact dimensions of the vectors and matrices of control law. The suggested technique is examined for linear and nonlinear physical systems. These systems are simulated using both the techniques to show the effectiveness of proposed control method. The rest of the paper is organized as follows. In Section II, overview of modified FOS feedback is presented. In Section III, proposed control method is discussed with software implementation aspects. Section IV discusses application of control to numerical examples along with simulation results. Finally paper is concluded in Section V.

II. A Modified Fast Output Sampling Feedback

Modified FOS feedback control technique is well elaborated in [3], [4]. However, for brevity it is discussed in the following. Consider MIMO continuous-time system

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z}(t) + \mathbf{B}\mathbf{u}(t), \tag{1}$$

$$\mathbf{y}(t) = \mathbf{C}\mathbf{z}(t) \tag{2}$$

where $\mathbf{z} \in \Re^n$ is the state, $\mathbf{u} \in \Re^m$ is the control and $\mathbf{y} \in \Re^p$ is the output. Matrices $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ are of appropriate matrix sizes. The system (1)-(2) is also assumed to be controllable and observable. If it is sampled at the rate of $1/\tau$, following discrete-time system is obtained

$$\mathbf{z}((k+1)\tau) = \mathbf{\Phi}_\tau \mathbf{z}(k\tau) + \mathbf{\Gamma}_\tau \mathbf{u}(k\tau), \tag{3}$$

$$\mathbf{y}(k\tau) = \mathbf{C}\mathbf{z}(k\tau) \tag{4}$$

where $\mathbf{\Phi}_\tau = e^{\mathbf{A}\tau}$ and $\mathbf{\Gamma}_\tau = \int_0^\tau e^{\mathbf{A}s}\mathbf{B}ds$. Also suppose

$$\mathbf{z}((k+1)\Delta) = \mathbf{\Phi}_\Delta \mathbf{z}(k\Delta) + \mathbf{\Gamma}_\Delta \mathbf{u}(k\Delta) \tag{5}$$

be the discrete-time system corresponding to (1), when sampled at Δ sampling interval. Here $\Delta = \tau/N$ with $N \geq \nu$, in which ν is observability index [6] of (1)-(2). In FOS, the output measurements are taken at time instants $t = l\Delta$, $l = 0, 1, \ldots, N-1$. The control signal applied during the interval $k\tau < t \leq (k+1)\tau$ is constructed as a linear combination of the last N output observations. Then

$$\mathbf{z}((k+1)\tau) = \mathbf{\Phi}_\tau \mathbf{z}(k\tau) + \mathbf{\Gamma}_\tau \mathbf{u}(k\tau) \tag{6}$$

$$\mathbf{y}_{k+1} = \mathbf{C_0}\mathbf{z}(k\tau) + \mathbf{D_0}\mathbf{u}(k\tau) \tag{7}$$

where $\mathbf{y}_k$, $\mathbf{C_0}$ and $\mathbf{D_0}$ are given by

$$\mathbf{y}_k = \begin{bmatrix} \mathbf{y}((k-1)\tau) \\ \mathbf{y}((k-1)\tau+\Delta) \\ \vdots \\ \mathbf{y}(k\tau-\Delta) \end{bmatrix}, \tag{8}$$

$$\mathbf{C_0} = \begin{bmatrix} \mathbf{C} \\ \mathbf{C}\Phi_\Delta \\ \vdots \\ \mathbf{C}\Phi_\Delta^{N-1} \end{bmatrix}, \mathbf{D_0} = \begin{bmatrix} \mathbf{0} \\ \mathbf{C}\boldsymbol{\Gamma}_\Delta \\ \vdots \\ \mathbf{C}\Sigma_{i=0}^{N-2}\boldsymbol{\Phi}_\Delta^i\boldsymbol{\Gamma}_\Delta \end{bmatrix}. \tag{9}$$

Observablity of system (3) implies $rank(\mathbf{C_0}) = n$. Now, if N is chosen as greater than the observability index, then for p outputs, necessarily $Np \geq n$ and $\mathbf{C_0}$ would be of dimensions $(Np \times n)$. Thus, from (6) and (7) the state vector $\mathbf{z}(k\tau)$ can be obtained in terms of $\mathbf{y}_k$ and $\mathbf{u}((k-1)\tau)$ as

$$\mathbf{z}(k\tau) = \mathbf{L}_{\mathrm{y}}\mathbf{y}_k + \mathbf{L}_{\mathrm{u}}\mathbf{u}((k-1)\tau) \tag{10}$$

where

$$\mathbf{L}_{\mathrm{y}} = \boldsymbol{\Phi}_\tau(\mathbf{C_0}^T\mathbf{C_0})^{-1}\mathbf{C_0}^T, \tag{11}$$

$$\mathbf{L}_{\mathrm{u}} = \boldsymbol{\Gamma}_\tau - \boldsymbol{\Phi}_\tau(\mathbf{C_0}^T\mathbf{C_0})^{-1}\mathbf{C_0}^T\mathbf{D_0}. \tag{12}$$

It is evident from (10) that the state of the system (3) can be determined exactly from the past measurements of the output and one delayed input [3]. Let $\mathbf{F}$ be a state feedback gain matrix for the control input

$$\mathbf{u}(k\tau) = \mathbf{F}\mathbf{z}(k\tau) \tag{13}$$

so that the closed-loop system $(\boldsymbol{\Phi}_\tau + \boldsymbol{\Gamma}_\tau\mathbf{F})$ has eigenvalues in the unit circle. This can be changed into an output feedback merely by replacing $\mathbf{z}(k\tau)$ from (10) as

$$\mathbf{u}(k\tau) = \mathbf{F}\mathbf{L}_{\mathbf{y}}\mathbf{y}_k + \mathbf{F}\mathbf{L}_{\mathrm{u}}\mathbf{u}((k-1)\tau). \tag{14}$$

III. Proposed Control Technique

In this section, it is shown that the previous two control inputs can be used to calculate the current control input of the MIMO system along with multirate output observations. As a result, the overall performance of the closed loop system is enhanced. Also, the software implementation of this control with MATLAB/Simulink is explained for better understanding of algorithm.

A. Control Design Procedure

Let us consider the case with $n = 2$ and $N = 2$. Then $\mathbf{y}_k$ in (8) becomes

$$\mathbf{y}_k = \begin{bmatrix} \mathbf{y}((k-1)\tau) \\ \mathbf{y}((k-1)\tau+\Delta) \end{bmatrix}. \tag{15}$$

If one more past output i.e. $\mathbf{y}((k-1)\tau-\Delta)$ is included in (15), then $\mathbf{y}_k$ can be denoted as $\bar{\mathbf{y}}_k$ and given by

$$\bar{\mathbf{y}}_k = \begin{bmatrix} \mathbf{y}((k-1)\tau-\Delta) \\ \mathbf{y}((k-1)\tau) \\ \mathbf{y}((k-1)\tau+\Delta) \end{bmatrix}. \tag{16}$$

Using (4), $\bar{\mathbf{y}}_{k+1}$ can be rewritten as

$$\bar{\mathbf{y}}_{k+1} = \mathbf{C}\begin{bmatrix} \mathbf{z}(k\tau-\Delta) \\ \mathbf{z}(k\tau) \\ \mathbf{z}(k\tau+\Delta) \end{bmatrix} \tag{17}$$

where

$$\mathbf{z}(k\tau) = \boldsymbol{\Phi}_\Delta\mathbf{z}(k\tau-\Delta) + \boldsymbol{\Gamma}_\Delta\mathbf{u}(k-1)\tau), \tag{18}$$

$$\mathbf{z}(k\tau+\Delta) = \boldsymbol{\Phi}_\Delta\mathbf{z}(k\tau) + \boldsymbol{\Gamma}_\Delta\mathbf{u}((k\tau). \tag{19}$$

From (18), $\mathbf{z}(k\tau-\Delta)$ can be determined as

$$\mathbf{z}(k\tau-\Delta) = \boldsymbol{\Phi}_\Delta^{-1}\mathbf{z}(k\tau) - \boldsymbol{\Phi}_\Delta^{-1}\boldsymbol{\Gamma}_\Delta\mathbf{u}((k-1)\tau). \tag{20}$$

Now substituting (18)-(20) in (17) one can get

$$\bar{\mathbf{y}}_{k+1} = \bar{\mathbf{C}}_\mathbf{0}\mathbf{z}(k\tau) + \bar{\mathbf{D}}_\mathbf{0}\begin{bmatrix}\mathbf{u}((k-1)\tau) & \mathbf{u}(k\tau)\end{bmatrix}^T \tag{21}$$

where

$$\bar{\mathbf{C}}_\mathbf{0} = \begin{bmatrix} \mathbf{C}\boldsymbol{\Phi}_\Delta^{-1} \\ \mathbf{C} \\ \mathbf{C}\Phi_\Delta \end{bmatrix}, \bar{\mathbf{D}}_\mathbf{0} = \begin{bmatrix} -\mathbf{C}\boldsymbol{\Phi}_\Delta^{-1}\boldsymbol{\Gamma}_\Delta & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{C}\boldsymbol{\Gamma}_\Delta \end{bmatrix}. \tag{22}$$

When this is generalized for the system (3), then $\bar{\mathbf{C}}_\mathbf{0}$ and $\bar{\mathbf{D}}_\mathbf{0}$ of dimensions $((N+1)p \times n)$ and $((N+1)p \times 2m)$ respectively are constructed as

$$\bar{\mathbf{C}}_\mathbf{0} = \begin{bmatrix} \mathbf{C}\boldsymbol{\Phi}_\Delta^{-1} \\ \mathbf{C} \\ \mathbf{C}\boldsymbol{\Phi}_\Delta \\ \vdots \\ \mathbf{C}\boldsymbol{\Phi}_\Delta^{N-1} \end{bmatrix},$$

$$\bar{\mathbf{D}}_\mathbf{0} = \begin{bmatrix} -\mathbf{C}\boldsymbol{\Phi}_\Delta^{-1}\boldsymbol{\Gamma}_\Delta & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{C}\boldsymbol{\Gamma}_\Delta \\ \vdots & \vdots \\ \mathbf{0} & \mathbf{C}\Sigma_{i=0}^{N-2}\boldsymbol{\Phi}_\Delta^i\boldsymbol{\Gamma}_\Delta \end{bmatrix}. \tag{23}$$

Solving (21) for $\mathbf{z}(k\tau)$ and then substituting in (6), states can be determined as

$$\mathbf{z}(k\tau) = \bar{\mathbf{L}}_y\mathbf{y}_k + \bar{\mathbf{L}}_u\begin{bmatrix}\mathbf{u}((k-2)\tau) & \mathbf{u}((k-1)\tau)\end{bmatrix}^T \tag{24}$$

where matrices $\bar{\mathbf{L}}_{\mathrm{y}}$ and $\bar{\mathbf{L}}_{\mathrm{u}}$ are respectively of dimensions $(n \times (N+1)p)$ and $(n \times 2m)$ and are given by

$$\bar{\mathbf{L}}_{\mathrm{y}} = \boldsymbol{\Phi}_\tau(\bar{\mathbf{C}}_\mathbf{0}^T\bar{\mathbf{C}}_\mathbf{0})^{-1}\bar{\mathbf{C}}_\mathbf{0}^T, \tag{25}$$

$$\bar{\mathbf{L}}_{\mathrm{u}} = \begin{bmatrix}\mathbf{0} & \boldsymbol{\Gamma}_\tau\end{bmatrix} - \boldsymbol{\Phi}_\tau(\bar{\mathbf{C}}_\mathbf{0}^T\bar{\mathbf{C}}_\mathbf{0})^{-1}\bar{\mathbf{C}}_\mathbf{0}^T\bar{\mathbf{D}}_\mathbf{0} \tag{26}$$

where $\mathbf{0}$ in $\bar{\mathbf{L}}_{\mathrm{u}}$ is a null matrix of dimension $(n \times m)$. Finally using (13) and (24) control input can be given by

$$\mathbf{u}(k\tau) = \mathbf{F}\bar{\mathbf{L}}_y\mathbf{y}_k + \mathbf{F}\bar{\mathbf{L}}_u\begin{bmatrix}\mathbf{u}((k-2)\tau) \\ \mathbf{u}((k-1)\tau)\end{bmatrix}. \tag{27}$$

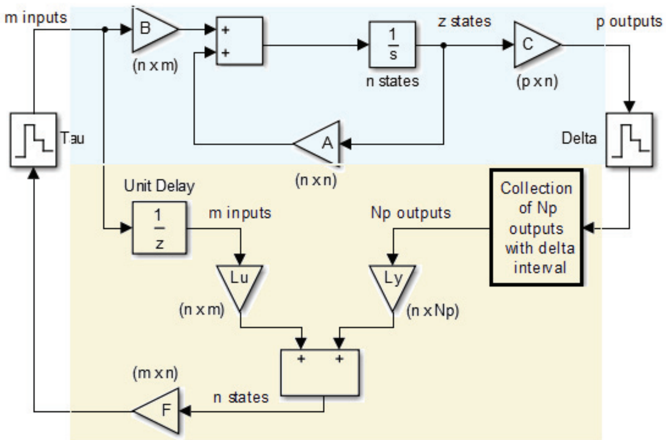

Fig. 1. Implementation scheme of modified FOS.

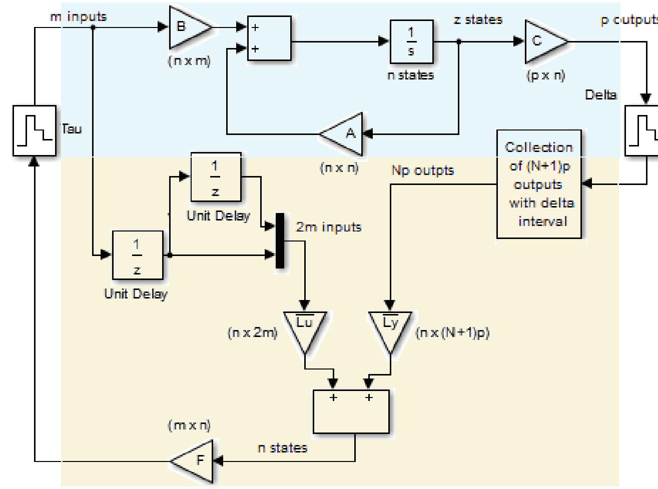

Fig. 2. Implementation scheme of proposed FOS.

B. Software Implementation Procedure

Control algorithms (14) of modified FOS and (27) of proposed FOS are applied separately to the system (1)-(2) using MATLAB/Simulink [7] as shown in Figs. 1 and 2 respectively. In these implementations, control scheme and plant/system are represented by different colors. In Fig. 1, p number of outputs are sampled at the rate of $1/\Delta$ during τ sampling interval. Recall that, $N = \tau/\Delta$, hence total Np number of outputs are stored and collectively applied to the gain $\mathbf{L_y}$, which is of dimension $(n \times Np)$. At the same time, m number of delayed inputs are obtained by using 'Unit Delay' block and multiplied with $(n \times m)$ matrix $\mathbf{L_y}$. Addition of these two signals generates n states as per (10), which are then given to state feedback $\mathbf{F}$ to generate control input. In Fig. 2, $(N+1)$ times p number of outputs are stacked. This includes, N times in the current sampling interval τ and the last set of outputs from $(\tau - 1)$ interval. These outputs are then combined and given to FOS gain $\bar{\mathbf{L}}_\mathbf{y}$ of dimension $(n \times (N+1)p)$. Again at the same instant, $2m$ number of inputs, obtained using two blocks of 'Unit Delay' (Fig. 2), are given as input to $(n \times 2m)$ matrix $\bar{\mathbf{L}}_\mathbf{y}$. These two signals are then added to calculate n states and thereby control input. It is important to note that, these software implementation schemes are applicable for n states, m inputs and p outputs (i.e. multi-input multi-output system), provided the multiplication option in the respective gain block is selected properly. Otherwise, it would result in the mismatch of dimension. For the nonlinear system implementation, linear system must be replaced with equivalent nonlinear system block.

IV. Numerical Examples

In this section, two numerical examples, representing the physical systems, are simulated using the proposed control algorithm. Out of these, first is linear system and the second is nonlinear system.

A. Linear System

Consider the linear model of nuclear reactor [1] with following system matrices.

$$\mathbf{A} = \begin{bmatrix} -0.0900 & 0 & 0.0900 & 0 \\ 0 & -0.0900 & 0 & 0.0900 \\ 9.4937 & 0 & -12.8840 & 3.3900 \\ 0 & 9.4937 & 3.3900 & -12.8840 \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0 & 1265.8 & 0 \\ 0 & 0 & 0 & 1265.8 \end{bmatrix}^T,$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}.$$

Eigenvalues of $\mathbf{A}$ are $(-16.3266, -9.5840, -0.0374, 0)$. The system is found to be controllable and observable having observability index as 4. Taking the same $\tau = 1$ s as that of [1]. So, $\Delta = 0.25$ s. The system (33)-(34) is discretized with τ and state feedback matrix $\mathbf{F}$ is determined using $\mathbf{Q} = 0.1\mathbf{E}_4$ and $\mathbf{R} = \mathbf{E}_2$ as

$$\mathbf{F} = \begin{bmatrix} 0.0106 & -0.0010 & 0.0001 & 0 \\ -0.0010 & 0.0106 & 0 & 0.0001 \end{bmatrix}.$$

Closed loop eigenvalues of the discrete τ system are noted to be $(0, 0, 0.8831, 0.8843)$ after the application of state feedback. For a modified FOS, $\mathbf{L_u}$ and $\mathbf{L_y}$ are calculated from (11) and (12) as

$$\mathbf{L_y} = \begin{bmatrix} -0.0002 & -0.0001 & 0.0035 & -0.0004 \\ -0.0001 & -0.0002 & -0.0004 & 0.0035 \end{bmatrix}$$
$$\begin{bmatrix} 0.0037 & -0.0002 & 0.0037 & -0.0002 \\ -0.0002 & 0.0037 & -0.0002 & 0.0037 \end{bmatrix}.$$

$$\mathbf{L_u} = \begin{bmatrix} 0.0562 & 0.0109 \\ 0.0109 & 0.0562 \end{bmatrix}$$

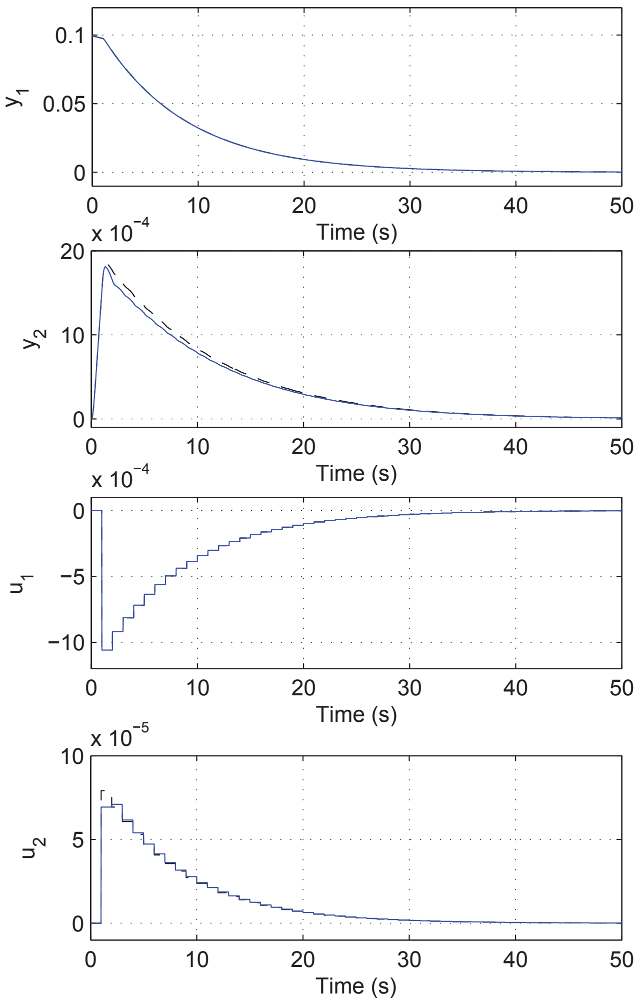

Fig. 3. Comparison of system outputs and control input (blue-dark indicates proposed FOS and black-dash indicates modified FOS).

and control structure given by (14), based on output observations and past input is given to linear model. For the proposed control $\bar{\mathbf{L}}_{\mathbf{u}}$ and $\bar{\mathbf{L}}_{\mathbf{y}}$ are computed from (25) and (26) as

$$\mathbf{L_y} = \begin{bmatrix} -0.0001 & -0.0001 & 0.0026 & -0.0003 & 0.0027 \\ -0.0001 & -0.0001 & -0.0003 & 0.0026 & -0.0002 \end{bmatrix.$$
$$\begin{matrix} -0.0002 & 0.0027 & -0.0002 & 0.0027 & -0.0001 \\ 0.0027 & -0.0002 & 0.0027 & -0.0001 & 0.0027 \end{bmatrix}.$$

$$\mathbf{L_u} = \begin{bmatrix} 0.0017 & 0.0005 & 0.0668 & 0.0125 \\ 0.0005 & 0.0017 & 0.0125 & 0.0668 \end{bmatrix}$$

and controller (27) is again applied to linear model. Simulation results are generated considering the initial condition $\mathbf{z}_0 = [0.1 \;\; 0 \;\; 0 \;\; 0]$. From Fig. 3 it is observed that the response with both the controllers is nearly same for y_1 and u_1 but small improvement can be seen for y_2 and u_2.

B. Nonlinear System

Inverted pendulum is taken as a nonlinear system for the simulation of control algorithm. It is described by

$$(M+m)\ddot{x} + b\dot{x} + ml\ddot{\theta}cos\theta - ml\dot{\theta}^2 sin\theta = u, \tag{28}$$
$$(J+ml^2)\ddot{\theta} + mglsin\theta + ml\ddot{x}cos\theta = 0. \tag{29}$$

All the symbols and their values are taken from [5]. Since, θ and $\dot{\theta}$ are very small, let $sin\theta \equiv \theta$, $cos\theta \equiv 1$, and $\dot{\theta}^2 = 0$. Then (28) and (29) can be linearized to get

$$(M+m)\ddot{x} + b\dot{x} + ml\ddot{\theta} = u, \tag{30}$$
$$(J+ml^2)\ddot{\theta} + mgl\theta + ml\ddot{x} = 0. \tag{31}$$

This linear system can be put into state-space form with state vector

$$\mathbf{z} = \begin{bmatrix} x & \dot{x} & \theta & \dot{\theta} \end{bmatrix}^T. \tag{32}$$

The angle θ represents the rotation of the pendulum rod and x is the location of the cart. These are considered as outputs of the system. With this, matrices $\mathbf{A}$, $\mathbf{B}$ and $\mathbf{C}$ are obtained as

$$\mathbf{A} = \begin{bmatrix} 0 & 1.0000 & 0 & 0 \\ 0 & 0 & -0.9401 & 0 \\ 0 & 0 & 0 & 1.0000 \\ 0 & 0 & 29.8615 & 0 \end{bmatrix}, \tag{33}$$

$$\mathbf{B} = \begin{bmatrix} 0 & 0.4167 & 0 & -1.1574 \end{bmatrix}^T, \tag{34}$$
$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}. \tag{35}$$

Eigenvalues of $\mathbf{A}$ are $(0, 0, 5.4646, -5.4646)$. Although the open loop system is unstable, it is controllable and observable. The observability index is 4. Sampling interval is selected as $\tau = 0.068$ s [5]. As a result, $\Delta = 0.017$ s. The system (33)-(34) is discretized with τ and feedback gain $\mathbf{F}$ is found using $\mathbf{Q} = 0.1\mathbf{E}_4$ and $\mathbf{R} = 1$ as

$$\mathbf{F} = [0.2143 \quad 0.9869 \quad 47.0396 \quad 8.6405].$$

Application of state feedback helps to move closed loop eigenvalues of the discrete τ system at $(0.6810, 0.6980, 0.9828 \pm i0.0159)$ i.e. asymptotically stable locations. For a modified approach of FOS, $\mathbf{L_u}$ and $\mathbf{L_y}$ are calculated from (11) and (12) as

$$\mathbf{L_y} = [-17.5234 \quad -176.8662 \quad -5.8085 \quad -49.0201$$
$$5.9197 \quad 78.4026 \quad 17.6265 \quad 206.5024],$$
$$\mathbf{L_u} = -0.4483,$$

and control (14), relying on output observations and previous input is applied to nonlinear model. For the proposed control $\bar{\mathbf{L}}_{\mathbf{u}}$ and $\bar{\mathbf{L}}_{\mathbf{y}}$ are calculated from (25) and (26) as

$$\bar{\mathbf{L}}_{\mathbf{y}} = [-11.6961 \quad -121.2344 \quad -5.8323 \quad -54.2733$$
$$0.0462 \quad 12.2190 \quad 5.9214 \quad 78.8169 \quad 11.7751 \quad 146.0955]$$
$$\bar{\mathbf{L}}_{\mathbf{u}} = [-0.0196 \quad -0.0631]$$

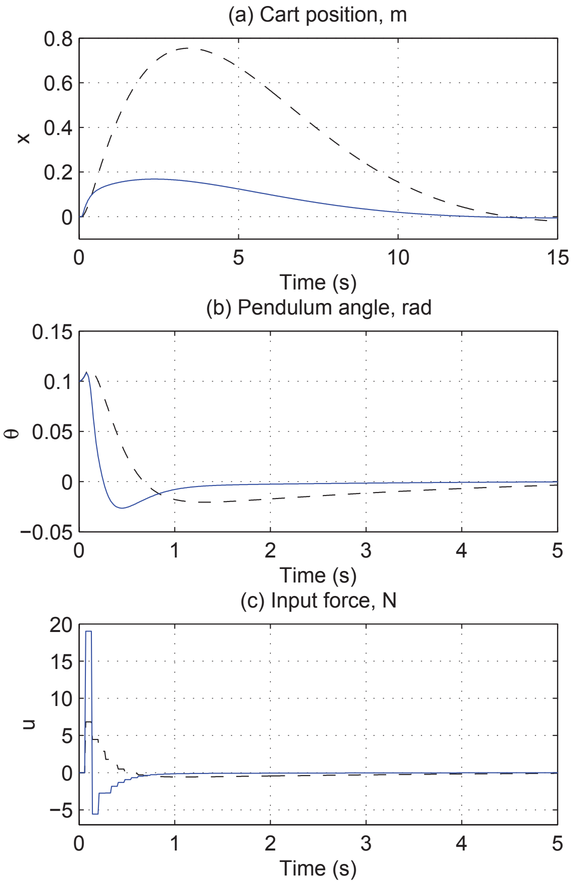

Fig. 4. Comparison of system outputs and control input (blue-dark indicates proposed FOS and black-dash indicates modified FOS).

and control (27) is also tested for nonlinear model. Simulation results are generated for the case of output regulation considering the initial condition $\mathbf{z}_0 = [0 \;\; 0 \;\; 0.1 \;\; 0]$. From Fig. 4, it is clearly seen that, the performance of the suggested controller is superior than the existing FOS controller. Although, the settling time for cart position is same for both the controllers, reduction in the overshoot with proposed control approach is significant (Fig. 4(a)). Also, the pendulum angle settles much earlier with the presented control scheme (Fig. 4(b)). Corresponding control inputs are shown in Fig. 4(c).

V. Conclusion

In this paper, new control technique based on modified FOS is suggested for multivariable system. This technique uses two consecutive delayed inputs to calculate current input. Due to which, the overall closed-loop behavior of the system is improved. Multivariable systems considered in this paper are linear and nonlinear physical systems. Performances are also compared with the conventional modified FOS technique to show the effectiveness of the proposed method. Realization of the controls with MATLAB/Simulink software is also discussed briefly. In future work, one can design robust control using sliding mode control using the presented approach.

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