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DISTURBANCE OBSERVER-BASED EXTENDED STATE CONVERGENCE ARCHITECTURE FOR MULTILATERAL TELEOPERATION SYSTEMS

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Abstract

In the existing extended state convergence architecture, k-master systems can control the motion of l-slave systems to perform a certain task in a remote environment. However, dependency of this control framework on systems' parameters leads to a degraded control performance in the presence of significant parameter variations. In this study, we have integrated extended state observers in extended state convergence architecture to counter the effect of uncertainties, which has resulted in a more practical architecture for multilateral teleoperation systems. In order to validate the proposed enhanced architecture, simulations are performed in MATLAB/Simulink environment by considering a symmetric (2×2) as well as asymmetric (2×1) teleoperation system. A comparative assessment with the existing state convergence architecture proves the superiority of the proposed architecture. In addition, hardware experimentation is carried out on Quanser QUBE-servo systems by setting up an asymmetric (1×2) teleoperation system in the QUARC environment.

Key Words

State convergence, extended state observer, teleoperation, MATLAB/QUARC/Simulink

1. Introduction

Recent technological advancements, such as telecommunications, enhance human influence in a remote environment and bilateral teleoperation is an example of this framework, due to which it has become possible for a person to manipulate any task in a remote environment with improved perception, such as space and underwater exploration, and minimal invasive surgery. A conventional bilateral teleoperation system uses a pair of master and slave robots to execute the task. During the operation, motion commands and force signals are transmitted over a time-delayed channel, which is the main source of instability in teleoperation systems. Initial research has been directed to overcome this instability issue and seminal results are obtained using scattering theory and wave variables [1], [2]. Several studies have been conducted afterwards aiming to reduce their conservatism [3], improving the transparency [4], [5], and extension to multi-DOF systems [6]. A method to assign desired dynamics to bilateral teleoperation is proposed in [7] and an associated study reports similar results with fewer communication channels [8]–[10]. More recently, researchers have designed multilateral teleoperation systems to improve the capability of their bilateral counterparts. Various multilateral topologies, intended for particular tasks have emerged which employ extended versions of bilateral control algorithms to deal with time delays and uncertainties [11]–[21].

This paper proposes an improved version of extended state convergence architecture [22] through the use of disturbance observers. The proposal enables the existing architecture to handle systems' uncertainties by treating them as disturbances and compensates their effects to improve the tracking performance. MATLAB simulations as well as experimental results prove the validity of the proposed architecture in establishing multilateral communication between k-master and l-slave systems. To the best of our knowledge, robustness improvement of extended state convergence architecture has not been reported in the literature.

This paper is structured as follows. Section 2 describes the proposed architecture and the associated design procedure is presented in Section 3. Simulation and

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Table 1
Notations Describing Observer-Based Extended State Convergence Architecture

Notation	Description	Notation	Description
F_{hk}	Force exerted by the k^{th} operator on the k^{th} master system	G_{slk}	Effect of the k^{th} operator's force in the l^{th} slave system
K_{mke}	Stabilising extended gain for the k^{th} master system	K_{sle}	Stabilising extended gain for the l^{th} slave system
R_{mkl}	Effect of motion of the l^{th} slave system in the k^{th} master system	R_{slk}	Effect of motion of $the k^{th}$ master system in the l^{th} slave system
L_{mke}	Extended state observer's gain for the k^{th} master system	L_{ske}	Extended state observer's gain for the l^{th} slave system

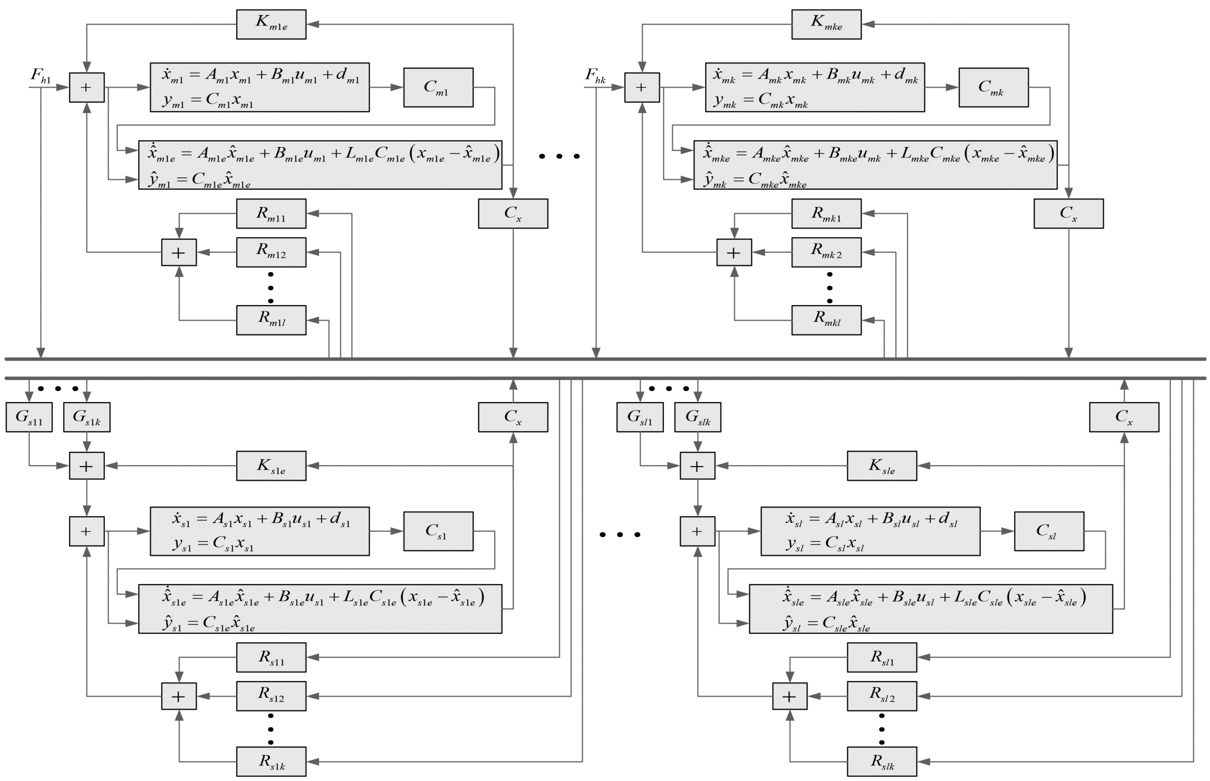

Figure 1. Proposed disturbance observer-based architecture.

experimental results are presented in Section 4 followed by conclusions.

2. Proposed Architecture

In extended state convergence architecture, $n\,(k+l) + (n+1)\,kl$ design conditions are required to be solved to determine the same number of control gains. In the proposed version, extra $(n+1)\,kl$ design conditions are required to be solved to determine disturbance observers' gains. Although, the computational cost is increased in the proposed architecture but its ability to deal with parameters variations is greatly improved. The proposed architecture is shown in Fig. 1. We include various notations describing the architecture in Table 1.

3. Design Procedure

The design methodology is a two-stage procedure in which augmented system containing closed-loop master and error systems is formed at the first step and then the augmented system is stabilised by placing the poles in the left half plane with error systems set as autonomous systems. Let master and slave systems $(z = m, s)$ be modelled on state space as:

$$\begin{aligned} \dot{x}_{zi} &= A_{zi}x_{zi} + d_{zi} \\ y_{zi} &= C_{zi}x_{zi} \end{aligned} \tag{1}$$

In (1), system and input matrices contain nominal plant values whereas parametric uncertainties are included as disturbance terms. We form extended master and slave systems by considering disturbance terms as additional states as:

$$\begin{aligned}\dot{x}_{zie} &= A_{zie}x_{zie} + B_{zie}u_{zi}\\ y_{zi} &= C_{zie}x_{zie}\end{aligned} \tag{2}$$

To estimate master and slave systems' states, including disturbances, extended state observers are designed as:

$$\begin{aligned}\dot{\widehat{x}}_{zie} &= A_{zie}\widehat{x}_{zie} + B_{zie}u_{zi} + L_{zie}\left(\widehat{y}_{zi}\right)\\ \widehat{y}_{zi} &= C_{zie}\widehat{x}_{zie}\end{aligned} \tag{3}$$

The control inputs for the k^{th} master and the l^{th} slave systems are introduced as:

$$u_{mk} = K_{mke}\widehat{x}_{mke} + \sum_{i=1}^{l} R_{mki}\widehat{x}_{si}\left(t - T_{mki}\right) + F_{hk} \tag{4}$$

$$\begin{aligned}u_{sl} &= K_{sle}\widehat{x}_{sle} + \sum_{i=1}^{k} R_{sli}\widehat{x}_{mi}\left(t - T_{sli}\right)\\ &+ \sum_{i=1}^{k} G_{sli}F_{hi}\left(t - T_{sli}\right)\end{aligned} \tag{5}$$

In (4) and (5), the last element of stabilising gain, K_{zie} compensates for the parameter variations. By plugging (4) and (5) in (1), closed-loop master and slave systems are obtained as:

$$\begin{aligned}\dot{x}_{mk} &= \left(A_{mk} + B_{mk}K_{mk}\right)x_{mk}\\ &+ \sum_{i=1}^{l} B_{mk}R_{mki}x_{si}\left(t - T_{mki}\right)\\ &+ B_{mk}F_{hk} + e_{dmk}\end{aligned} \tag{6}$$

$$\begin{aligned}\dot{x}_{sl} &= \left(A_{sl} + B_{sl}K_{sl}\right)x_{sl} + \sum_{i=1}^{k} B_{sl}R_{sli}x_{mi}\left(t - T_{sli}\right)\\ &+ \sum_{i=1}^{k} B_{sl}G_{sli}F_{hi}\left(t - T_{sli}\right) + e_{dsl}\end{aligned} \tag{7}$$

In (6) and (7), e_{dzi} contains estimation error terms. Using Taylor expansion on time-delayed signals in (6), (7), and discarding higher-order terms, we get:

$$\begin{bmatrix}\dot{x}_{m1}\\ \vdots\\ \dot{x}_{mk}\\ \dot{x}_{s1}\\ \vdots\\ \dot{x}_{sl}\end{bmatrix} = \begin{bmatrix}A_{m1}+B_{m1}K_{m1} & \dots & 0 & B_{m1}R_{m11} & \dots & B_{m1}R_{m1l}\\ & \ddots & & & \vdots & \\ 0 & \dots & A_{mk}+B_{mk}K_{mk} & B_{mk}R_{mk1} & \dots & B_{mk}R_{mkl}\\ B_{s1}R_{s11} & \dots & B_{s1}R_{s1k} & A_{s1}+B_{s1}K_{s1} & \dots & 0\\ & \vdots & & & \ddots & \\ B_{sl}R_{sl1} & \dots & B_{sl}R_{slk} & 0 & \dots & A_{sl}+B_{sl}K_{sl}\end{bmatrix}\begin{bmatrix}x_{m1}\\ \vdots\\ x_{mk}\\ x_{s1}\\ \vdots\\ x_{sl}\end{bmatrix} -$$

$$\begin{bmatrix}0 & \dots & 0 & B_{m1}T_{m11}R_{m11} & \cdots & B_{m1}T_{m1l}R_{m1l}\\ & \vdots & & & \vdots & \\ 0 & \dots & 0 & B_{mk}T_{mk1}R_{mk1} & \dots & B_{mk}T_{mkl}R_{mkl}\\ B_{s1}T_{s11}R_{s11} & \dots & B_{s1}T_{s1k}R_{s1k} & 0 & \dots & 0\\ & \vdots & & & \vdots & \\ B_{sl}T_{sl1}R_{sl1} & \dots & B_{sl}T_{slk}R_{slk} & 0 & \dots & 0\end{bmatrix}\begin{bmatrix}\dot{x}_{m1}\\ \vdots\\ \dot{x}_{mk}\\ \dot{x}_{s1}\\ \vdots\\ \dot{x}_{sl}\end{bmatrix} + \begin{bmatrix}B_{m1} & \dots & 0\\ & \ddots & \\ 0 & \dots & B_{mk}\\ B_{s1}G_{s11} & \dots & B_{s1}G_{s1k}\\ & \vdots & \\ B_{sl}G_{sl1} & \dots & B_{sl}G_{slk}\end{bmatrix}\begin{bmatrix}F_{h1}\\ \vdots\\ F_{hk}\end{bmatrix} + \begin{bmatrix}e_{dm1}\\ \vdots\\ e_{dmk}\\ e_{ds1}\\ \vdots\\ e_{dsl}\end{bmatrix} \tag{8}$$

Let us define the following matrices:

$$\begin{aligned}x_m &= \begin{bmatrix}x_{m1} & \dots & x_{mk}\end{bmatrix}^T, x_s = \begin{bmatrix}x_{s1} & \dots & x_{sl}\end{bmatrix}^T,\\ A_m &= diag\left(A_{m1}, \dots, A_{mk}\right), A_s = diag\left(A_{s1}, \dots, A_{sl}\right)\\ B_m &= diag\left(B_{m1}, \dots, B_{mk}\right), B_s = diag\left(B_{s1}, \dots, B_{sk}\right),\\ K_m &= diag\left(K_{m1}, \dots, K_{mk}\right), K_s = diag\left(K_{s1}, \dots, K_{sl}\right)\\ R_m &= \begin{bmatrix}R_{m11} & \dots & R_{m1l}\\ & \vdots & \\ R_{mk1} & \dots & R_{mkl}\end{bmatrix}, R_s = \begin{bmatrix}R_{s11} & \dots & R_{s1k}\\ & \vdots & \\ R_{sl1} & \dots & R_{slk}\end{bmatrix},\\ T_m &= \begin{bmatrix}T_{m11} & \dots & T_{m1l}\\ & \vdots & \\ T_{mk1} & \dots & T_{mkl}\end{bmatrix}, T_s = \begin{bmatrix}T_{s11} & \dots & T_{s1k}\\ & \vdots & \\ T_{sl1} & \dots & T_{slk}\end{bmatrix}\\ F_h &= \begin{bmatrix}F_{h1} & \dots & F_{hk}\end{bmatrix}^T, G_s = \begin{bmatrix}G_{s11} & \dots & G_{s1k}\\ & \vdots & \\ G_{sl1} & \dots & G_{slk}\end{bmatrix},\\ e_{dm} &= \begin{bmatrix}e_{dm1} & \dots & e_{dmk}\end{bmatrix}^T, e_{ds} = \begin{bmatrix}e_{ds1} & \dots & e_{dsl}\end{bmatrix}^T\end{aligned} \tag{9}$$

With the help of (9), we can write (8) in compact form as:

$$\begin{aligned}&\begin{bmatrix}I_{nk} & T_m \circ \left(B_m R_m\right)\\ T_s \circ \left(B_s R_s\right) & I_{nl}\end{bmatrix}\begin{bmatrix}\dot{x}_m\\ \dot{x}_s\end{bmatrix}\\ &= \begin{bmatrix}A_m + B_m K_m & B_m R_m\\ B_s R_s & A_s + B_s K_s\end{bmatrix}\begin{bmatrix}x_m\\ x_s\end{bmatrix}\\ &+ \begin{bmatrix}B_m\\ B_s G_s\end{bmatrix} F_m + \begin{bmatrix}e_{dm}\\ e_{ds}\end{bmatrix}\end{aligned} \tag{10}$$

In (8), operator '∘' denotes Hadamard product. By defining, $D_m = T_m \circ (B_m R_m), D_s = T_s \circ (B_s R_s)$, we can further simplify (10) as:

$$\begin{bmatrix} \dot{x}_m \\ \dot{x}_s \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_m \\ x_s \end{bmatrix} + \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} F_h \quad (11)$$

$$\begin{aligned} A_{11} &= (I_{nk} - D_m D_s)^{-1} K_m - D_m (I_{nl} - D_s D_m)^{-1} B_s R_s, \\ A_{12} &= (I_{nk} - D_m D_s)^{-1} B_m R_m - D_m (I_{nl} - D_s D_m)^{-1} K_s \\ A_{21} &= -D_s (I_{nk} - D_m D_s)^{-1} K_m - (I_{nl} - D_s D_m)^{-1} B_s R_s, \\ A_{22} &= -D_s (I_{nk} - D_m D_s)^{-1} B_m R_m - (I_{nl} - D_s D_m)^{-1} K_s \\ B_1 &= (I_{nk} - D_m D_s)^{-1} B_m - D_m (I_{nl} - D_s D_m)^{-1} B_s G_s, \\ B_2 &= -D_s (I_{nk} - D_m D_s)^{-1} B_m - (I_{nl} - D_s D_m)^{-1} B_s G_s \end{aligned} \quad (12)$$

We now transform the augmented system (11) into a new augmented system with tracking errors defined on the slave systems. To this end, the following linear transformation is introduced:

$$\begin{bmatrix} x_m \\ x_e \end{bmatrix} = \begin{bmatrix} I_{nk} & 0 \\ - & I_{nl} \end{bmatrix} \begin{bmatrix} x_m \\ x_s \end{bmatrix} \quad (13)$$

In (13), matrix A contains authority factors exercised by master systems to influence slave systems and is given as:

$$= \begin{bmatrix} \alpha_{11} I_n & \alpha_{12} I_n & ... & \alpha_{1k} I_n \\ \alpha_{21} I_n & \alpha_{22} I_n & ... & \alpha_{2k} I_n \\ & & \vdots & \\ \alpha_{l1} I_n & \alpha_{l2} I_n & ... & \alpha_{lk} I_n \end{bmatrix} \quad (14)$$

The time derivative of (13) along with (11) yields transformed augmented system as:

$$\begin{bmatrix} \dot{x}_m \\ \dot{x}_e \end{bmatrix} = \begin{bmatrix} \widetilde{A}_{11} & \widetilde{A}_{12} \\ \widetilde{A}_{21} & \widetilde{A}_{22} \end{bmatrix} \begin{bmatrix} x_m \\ x_e \end{bmatrix} + \begin{bmatrix} \widetilde{B}_1 \\ \widetilde{B}_2 \end{bmatrix} F_m \quad (15)$$

$$\begin{aligned} \widetilde{A}_{11} &= A_{11} + A_{12}, \widetilde{A}_{12} = A_{12}, \widetilde{A}_{21} \\ &= (A_{21} - A_{11}) + (A_{22} - A_{12}) \\ \widetilde{A}_{22} &= A_{22} - A_{12}, \widetilde{B}_1 = B_1, \widetilde{B}_2 = B_2 - B_1 \end{aligned} \quad (16)$$

According to the method of state convergence, an error should evolve as an autonomous system and the stability of the augmented system is ensured by placing poles of closed-loop master and error systems on the left half plane. This gives rise to the following design conditions whose solution returns control gains of the extended state convergence architecture:

$$\begin{aligned} \widetilde{A}_{21} &= 0, \widetilde{B}_2 = 0, \left| sI_{nk} - \widetilde{A}_{11} \right| \times \left| sI_{nl} - \widetilde{A}_{22} \right| \\ &= |sI_{nk} - P| \times |sI_{nl} - Q| \end{aligned} \quad (17)$$

In (17), matrices P and Q contain poles locations. Observer gains are found independently of the controller gains and no augmented system is formed to determine these gains.

4. Results and Discussion

In order to validate the proposed architecture, simulations are performed in MATLAB/Simulink environment by considering symmetric and asymmetric configurations of teleoperation systems. The following master and slave systems are considered where x_{zi}^1 and x_{zi}^2 are the position and velocity signals:

$$\begin{aligned} m_i &: \begin{cases} \dot{x}_{mi}^1 = x_{mi}^2 \\ \dot{x}_{mi}^2 = -\beta_{mi} \sin\left(x_{mi}^1\right) - 7.1429 x_{mi}^2 + 0.2656 u_{mi} \end{cases} \\ s_i &: \begin{cases} \dot{x}_{si}^1 = x_{si}^2 \\ \dot{x}_{si}^2 = -\beta_{si} \sin\left(x_{si}^1\right) - 6.25 x_{si}^2 + 0.2729 u_{si} \end{cases} \end{aligned} \quad (18)$$

First, consider a symmetrical 2×2 teleoperation system. To compute the controller and observer gains for this configuration, the following nominal models are assumed:

$$\begin{aligned} A_{m1} &= \begin{bmatrix} 0 & 1 \\ 0 & -7.0 \end{bmatrix}, A_{m2} = \begin{bmatrix} 0 & 1 \\ 0 & -5.0 \end{bmatrix}, \\ A_{s1} &= \begin{bmatrix} 0 & 1 \\ 0 & -4.0 \end{bmatrix}, A_{s2} = \begin{bmatrix} 0 & 1 \\ 0 & -6.0 \end{bmatrix} \\ B_{m1} &= \begin{bmatrix} 0 \\ 0.2 \end{bmatrix}, B_{m2} = \begin{bmatrix} 0 \\ 0.1 \end{bmatrix}, \\ B_{s1} &= \begin{bmatrix} 0 \\ 0.4 \end{bmatrix}, B_{s2} = \begin{bmatrix} 0 \\ 0.3 \end{bmatrix} \end{aligned} \quad (19)$$

Further, slaves are interacting with environments having stiffness as $k_{ei} = 10 \;\; Nms/rad$ and force feedback gains are assumed to be 0.1 which yields, $R_{mkl} = \begin{bmatrix} 0.1 & 0 \end{bmatrix}$. Time delays are ignored during the computation but will be considered during the simulations. Characteristic polynomial for the closed-loop master system is selected as $s^4 + 28s^3 + 292s^2 + 1344s + 2304 = 0$ while for error systems, it is selected as $s^4 + 31s^3 + 354s^2 + 1764s + 3240 = 0$. Design conditions (17) are solved using MATLAB symbolic toolbox with nominal models (19) and authority factors, $\alpha_{11} = 0.6, \alpha_{12} = 0.4, \alpha_{21} = 0.7, \alpha_{22} = 0.3$, which yields the following control gains:

$$\begin{aligned} G_{s11} &= 0.3, G_{s12} = 0.1, G_{s21} = 0.4667, G_{s22} = 0.1 \\ K_{m1} &= \begin{bmatrix} -321.5036 & -45.0226 \end{bmatrix}, \\ K_{m2} &= \begin{bmatrix} -360.4739 & -69.9548 \end{bmatrix} \\ K_{s1} &= \begin{bmatrix} -224.6373 & -37.5033 \end{bmatrix}, \\ K_{s2} &= \begin{bmatrix} -119.4145 & -19.9956 \end{bmatrix} \\ R_{s11} &= \begin{bmatrix} 38.8513 & 4.4952 \end{bmatrix}, \\ R_{s12} &= \begin{bmatrix} 54.0875 & 7.0058 \end{bmatrix} \\ R_{s21} &= \begin{bmatrix} -65.7082 & -9.3470 \end{bmatrix}, \end{aligned}$$

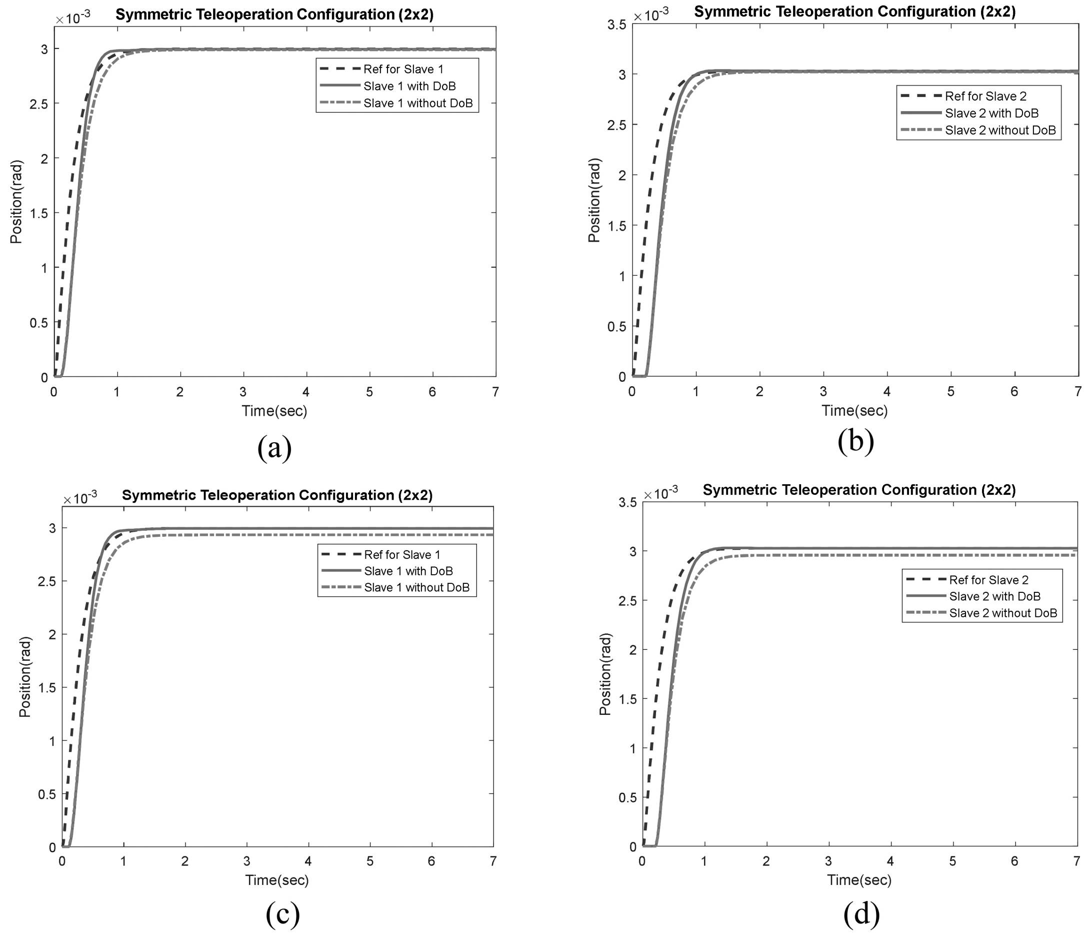

Figure 2. Symmetric teleoperation system: (a), (b) slave systems tracking performance with low level of disturbance; (c), (d) slave systems tracking performance with increased disturbance activity.

$$R_{s22} = \begin{bmatrix} 0.1736 & 0.0032 \end{bmatrix} \tag{20}$$

Observer gains are determined by placing the poles of the extended master and slave systems at $(s+30)^3$. This, in combination with (19), yields the following observer gains:

$$\begin{aligned} L_{m1e} &= \begin{bmatrix} 83 & 2119 & 27000 \end{bmatrix}^T, L_{m2e} = \begin{bmatrix} 85 & 2275 & 27000 \end{bmatrix}^T \\ L_{s1e} &= \begin{bmatrix} 86 & 2356 & 27000 \end{bmatrix}^T, L_{s2e} = \begin{bmatrix} 84 & 2196 & 27000 \end{bmatrix}^T \end{aligned} \tag{21}$$

Simulations are now performed by considering constant operator forces of 1 N and communication time delays as {0.1s, 0.2s}. Results of the proposed as well as existing architecture are recorded for various levels of disturbances and displayed in Fig. 2. It can be observed that existing architecture, which does not have disturbance observers, offers good tracking performance in the presence of parameter mismatches of (18) and (19) with $\beta_{\mathbf{zi}}$=**0.1** [Fig. 2(a) and (b)]. However, as the magnitude of β_{zi} is increased, the reference tracking performance of the existing extended convergence architecture is affected while the proposed disturbance observer-based version of the said architecture maintains good performance [Fig. 2(c) and (d)]. Note that, in these simulations, reference for the slaves are set as $x^1_{s1,ref} = \alpha_{11}x^1_{m1} + \alpha_{12}x^1_{m2}$ and$x^1_{s2,ref} = \alpha_{21}x^1_{m1} + \alpha_{22}x^1_{m2}$.

Now, we consider an asymmetrical 2×1 teleoperation system (18) with the following nominal plant models:

$$\begin{aligned} A_{m1} &= \begin{bmatrix} 0 & 1 \\ 0 & -9.2858 \end{bmatrix}, A_{m2} = \begin{bmatrix} 0 & 1 \\ 0 & -8.5715 \end{bmatrix}, A_{s1} = \begin{bmatrix} 0 & 1 \\ 0 & -5.0 \end{bmatrix} \\ B_{m1} &= \begin{bmatrix} 0 \\ 0.3187 \end{bmatrix}, B_{m2} = \begin{bmatrix} 0 \\ 0.3187 \end{bmatrix}, B_{s1} = \begin{bmatrix} 0 \\ 0.2183 \end{bmatrix} \end{aligned} \tag{22}$$

Let the stiffness of slave's environment be $k_e = 20\ Nms/rad$ and let the force feedback gain be 0.1. This gives rise to $R_{m11} = R_{m12} = \begin{bmatrix} 2.0 & 0 \end{bmatrix}$. Let desired polynomials for the master and error systems be $p(s) : s^4 + 13s^3 + 58.25s^2 + 110s + 75 = 0$ and $q(s) : s^2 + 15s + 54 = 0$. Communication time delays are assumed to be 1 ms during design phase while authority factors are taken to be $\alpha_{11} = 0.6, \alpha_{12} = 0.4$.

Solution of design conditions (17) yields the following control gains:

$$\begin{aligned} G_{s11} &= 0.970, G_{s12} = 0.6197, \\ K_{s1} &= \begin{bmatrix} -244.1640 & -45.8361 \end{bmatrix} \\ K_{m1} &= \begin{bmatrix} -15.6970 & 15.6791 \end{bmatrix}, \end{aligned}$$

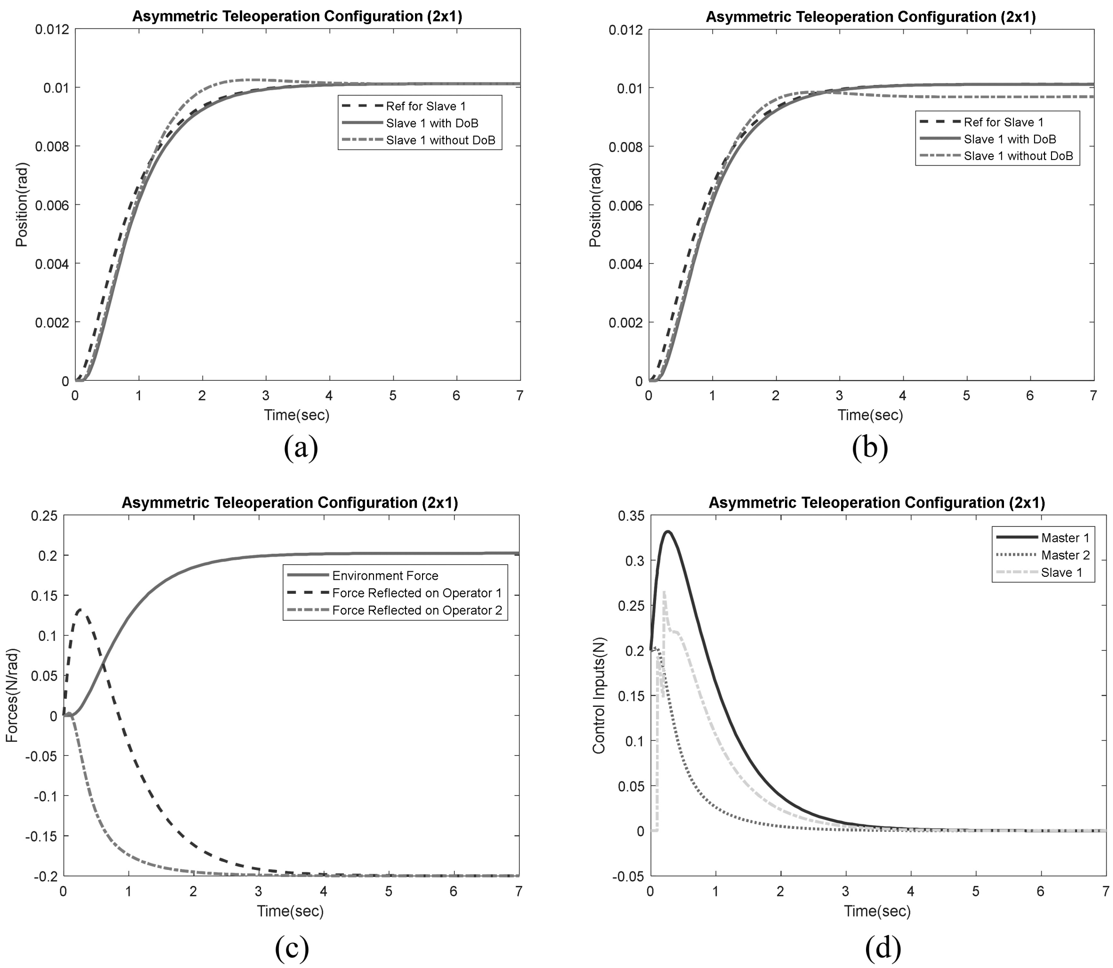

Figure 3. Asymmetric teleoperation system (a) Slave position tracking performance with parameter mismatches (β_{zi}=0) (b) Slave tracking performance with additional disturbance (β_{zi}=0.2)(c), (d) Force reflection ability of the proposed scheme and control inputs.

$$
\begin{aligned}
K_{m2} &= \begin{bmatrix} -51.7952 & -0.4192 \end{bmatrix} \\
R_{s11} &= \begin{bmatrix} 133.1805 & 29.5044 \end{bmatrix}, \\
R_{s12} &= \begin{bmatrix} 66.8386 & 11.2246 \end{bmatrix}
\end{aligned} \tag{23}
$$

Disturbance observer gains are computed based on nominal models (22) and a desired polynomial of $o(s):(s+30)^3=0$:

$$
\begin{aligned}
L_{m1e} &= \begin{bmatrix} 80.71 & 1950.5 & 27000 \end{bmatrix}^T, \\
L_{m2e} &= \begin{bmatrix} 81.43 & 2002 & 27000 \end{bmatrix}^T, \\
L_{s1e} &= \begin{bmatrix} 85 & 2275 & 27000 \end{bmatrix}^T
\end{aligned} \tag{24}
$$

Simulation results with operator's forces of 0.2 N, time delays of {0.1 s, 0.2 s}, and varying levels of disturbances are included in Fig. 3. It can be seen that the proposed architecture can establish communication between master and slave systems with good position tracking and force reflection abilities.

We also evaluate the tracking performance when time-varying delays exist in the communication channel. To this end, the asymmetric teleoperation system in (22)–(24) is simulated in the presence of time-varying delays and time-varying operators' forces and results are depicted in Fig. 4. It can be seen that the proposed scheme can establish communication between master and slave systems with varying communication delays.

Finally, experimental results are obtained using Qube-Servos manufactured by Quanser. Here, the asymmetric configuration is setup by using two real Qube-Servos while the master is a virtual device. The following nominal models are used for the controller and observer design:

$$
\begin{aligned}
A_{m1} &= \begin{bmatrix} 0 & 1 \\ 0 & -8.6710 \end{bmatrix}, A_{s1} = A_{s2} = \begin{bmatrix} 0 & 1 \\ 0 & -6.67 \end{bmatrix}, \\
B_{m1} &= \begin{bmatrix} 0 \\ 179.208 \end{bmatrix}, B_{s1} = B_{s2} = \begin{bmatrix} 0 \\ 149.34 \end{bmatrix}
\end{aligned} \tag{25}
$$

By assuming a soft environment with a stiffness of 1 Nms/rad, force feedback gain of 0.1, unity authority factor, no communication delays, $p(s):(s+5)^2=0$ as desired polynomial for master, $q(s):(s+10)^4=0$ as desired polynomial for error systems, and $o(s):(s+30)^3=0$ as

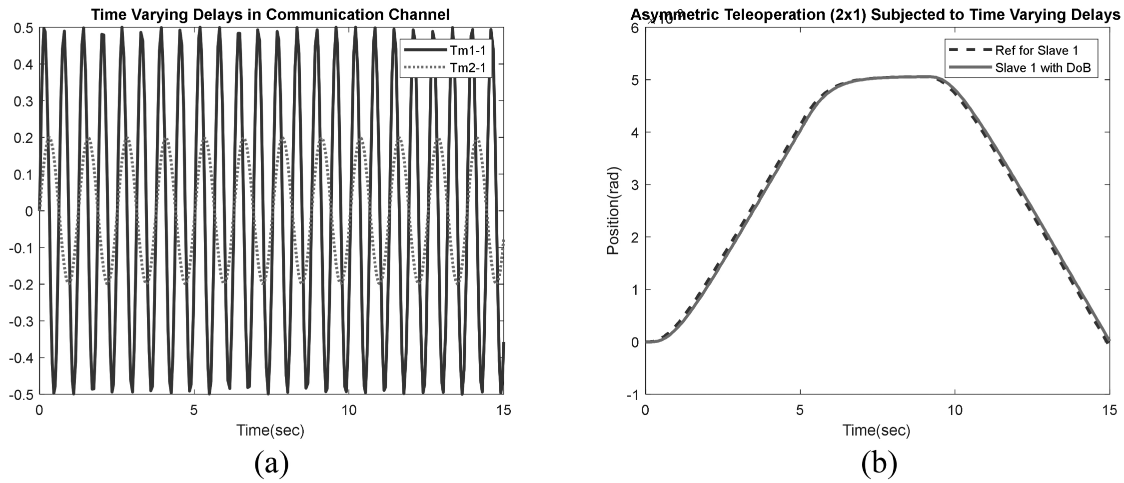

Figure 4. Asymmetric teleoperation system with time-varying delays: (a) time-varying delays of the communication channel; (b) slave position tracking performance with variable time delays.

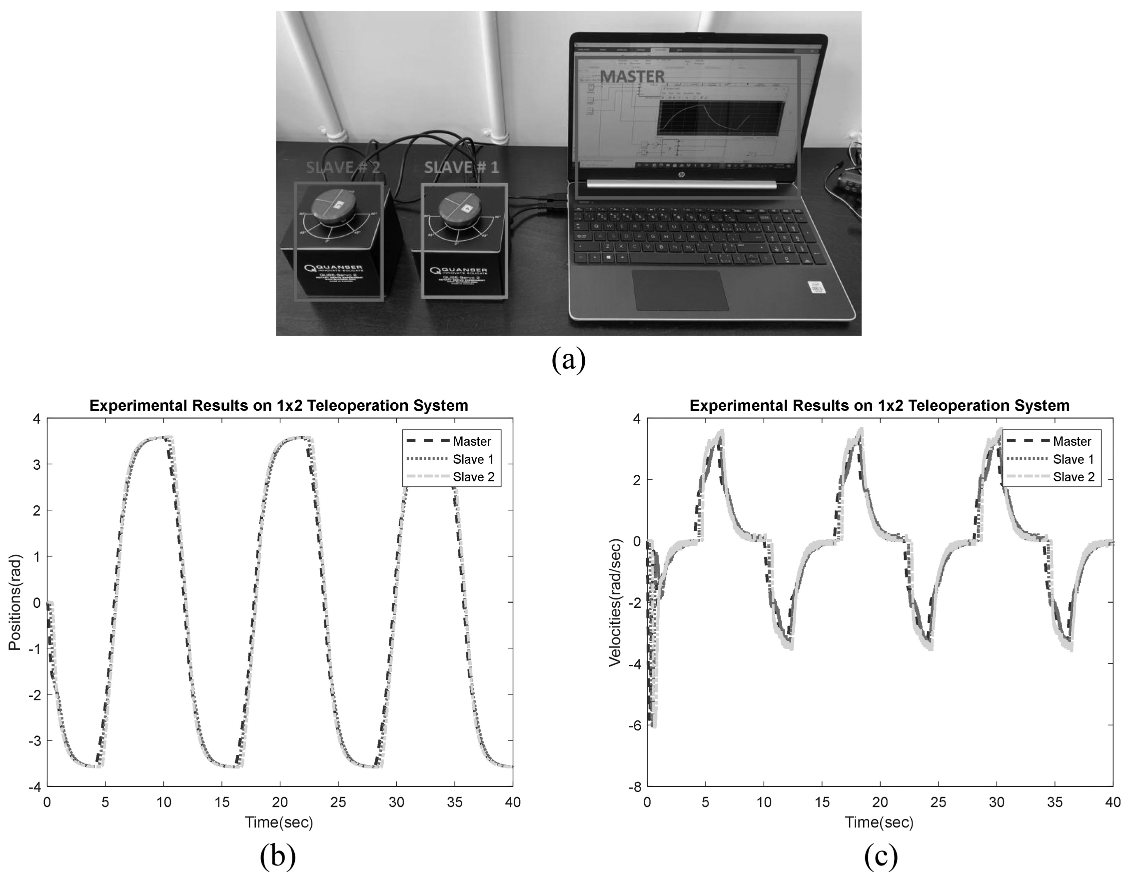

Figure 5. Experimental results on asymmetric teleoperation system: (a) experimental setup; (b) position states; (c) velocity states.

desired polynomial for observers, we obtain the following controller and observer gains:

$$
\begin{aligned}
G_{s11} &= G_{s21} = 1.2, K_{m1} = \begin{bmatrix} -0.3395 & -0.0074 \end{bmatrix}, \\
K_{s1} &= \begin{bmatrix} -1.0705 & -0.1293 \end{bmatrix}, K_{s2} = \begin{bmatrix} -0.2687 & -0.0492 \end{bmatrix} \\
R_{s11} &= \begin{bmatrix} 0.9031 & 0.1070 \end{bmatrix}, R_{s21} = \begin{bmatrix} 0.1013 & 0.0269 \end{bmatrix}
\end{aligned}
$$

$$
\begin{aligned}
L_{m1e} &= \begin{bmatrix} 81.329 & 1994.8 & 27000 \end{bmatrix}^T, \\
L_{s1e} &= L_{s2e} = \begin{bmatrix} 83.33 & 2144.2 & 27000 \end{bmatrix}^T
\end{aligned}
\tag{26}
$$

To evaluate the performance of the proposed architecture, a time-varying operator force profile is generated using ramp signals and time-delayed communication (T_{m11}=T_{s11}=0.1s, T_{m12}=T_{s21}=0.2 s) is setup using UDP server and client blocks among three separate QUARC files. Only position signals and force signals are transmitted on the communication channel while velocity signals are obtained through derivative filtering of time-delayed position signals with cut-off frequency of 30 rad/s. Results of experimentation are recorded using QUARC blocks and displayed in Fig. 5 . It can be seen that slaves are tracking the motion of the master system in the presence of uncertainties which validates the proposed enhanced architecture.

5. Conclusion

This paper has presented the design of a disturbance observer-based extended state convergence architecture for multilateral teleoperation systems. A systematic procedure is presented to determine the controller and observer gains for synchronising k-master and l-slave systems. The proposed architecture has been validated through MATLAB simulations on the symmetric and asymmetric configurations of teleoperation systems. Finally, experimental results are also presented using Quanser's Qube-Servos platforms. Comparison with the existing extended state convergence architecture proves the superiority of the proposed architecture in dealing with uncertainties. In the future, the proposed architecture will be tested on multi-degrees-of-freedom systems.

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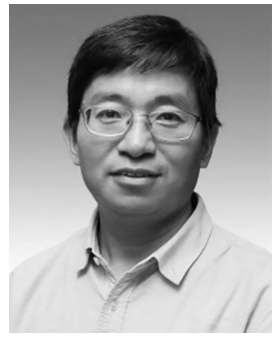

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