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# Bilateral Teleoperation with Nonlinear Environments: Multiplier Approach

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**Abstract:** The level of force transmitted to the human operator in bilateral teleoperation is being restricted due to the stability analysis methods. To increase telepresence, the multiplier approach has recently been exploited to analyse the absolute stability of the bilateral teleoperation where the environment is modelled as a bounded monotonic nonlinearity (Tugal et al., 2016). In this paper, we extend this methodology to 3-Channel architecture. The benefits of this methodology are demonstrated with experimental results, in particular we show that an improvement of the transparency index without stability degradation.

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*Keywords:* Teleoperation, Telerobotics, Passivity, Absolute stability, Multipliers.

## 1. INTRODUCTION

Teleoperation enables us to operate tasks located at a distance via robotic manipulators. If this process is carried out with bilateral architecture, then the operator receives tactile information when distance manipulator referred to as slave interacts with its environment. Motivation for the extra feedback channel is distinct: two way information flow increases situational awareness of the operator, thus quality of the performed task is increased alongside with reduction on the task's completion time, see Hannaford et al. (1991). Therefore, it becomes essential for the operations that require precision such as telesurgery, and applications conducted in hazardous environments like space activities, underwater exploration, or radioactive material handling.

Position tracking and transparency are the two main performance specifications in bilateral teleoperation. The former defines how well the slave pursues commands of the local manipulator referred to as master, and later defines the level of operator's telepresence by measuring precision of the transmitted environmental interaction force or task impedance to the master side. Besides them, absolute stability is one of the main argument while designing a bilateral teleoperation as design demand robustness of the highly uncertain and variable human-environment pair. Moreover, a further difficulty consists due to the trade-off between stability and transparency (Lawrence, 1993).

The dominated tendency for obtaining stability condition of a bilateral teleoperation is to use network theory along with passivity assumption (Llewellyn, 1952). Modelling obstacle of the human and environment is circumvented because once these operators are assumed to be passive, then stability of the overall system can be analysed by its input-output port information and without considering what will be the parameters of the models (Hokayem and Spong, 2006). The price to pay for these convenient approaches is conservatism of the designs as the overall system needs to be robust against a wide class of uncertain human and environment, such that it was analytically indicated that the Position-Force (P-F) architecture with PD controller, known for its simplicity, is not absolutely stable (Willaert et al., 2010). Consequently, within the same methodology there have been attempts to increase performance without jeopardising the stability by reducing the uncertainties' bounds, yet these promising approaches lag behind due to the required linearity assumption (Haddadi and Hashtrudi-Zaad, 2010).

Polat and Scherer (2012) have revealed the equivalence of the mentioned standard approaches and Integral Quadratic Constraints (IQC) framework, which illuminates the green light to extend uncertainties' assumptions, while analysing stability of the teleoperation. Based on this, combination of the IQC and Multiplier theories pawed the way absolutely stable bilateral teleoperation against more immense uncertain environment class, see Tugal et al. (2015) for the preliminary results. More detailed and extended analyses were proposed in (Tugal et al., 2016), where stability of the teleoperation investigated with different multipliers and also experiments were carried out with manipulators located at two different countries. In this paper, we also assume that environment is a bounded monotone nonlinear operator. Zames-Falb multiplier is used to analyse stability against this class of uncertainty. Then, we extend our previous studies to the 3-Channel (3C) architecture. Further analyses were carried out to compare 3C Position-Force Force (P-FF) with 2C P-F architecture while both designs have PD-controllers at slave sides. Then, Phantom Omni manipulators were used for experimental validations. It is observed that performance specifications of the proposed 3-C is superior to 2-C architecture when master and slave manipulators have similar dynamics (Willaert et al., 2014).

The notation is standard. Let $\mathcal{L}_2^m[0,\infty)$ be the Hilbert space of all square integrable functions $f:[0,\infty)\to\mathbb{R}^m$. Given $T\in\mathbb{R}$, a truncation of the function $f$ at $T$ is given

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by $f_T(t) = f(t), \quad \forall t \leq T$ and $f_T(t) = 0, \quad \forall t > T$. The function $f$ belongs to the extended space $\mathcal{L}_{2e}^m[0,\infty)$ if $f_T \in \mathcal{L}_2^m[0,\infty)$ for all $T > 0$. The Fourier transform of $f$ is expressed by $\hat{f}(j\omega) = \int_0^\infty e^{-j\omega t} f(t)dt$.

Let $(\star)$ be a space holder for the right outer factor of a quadratic form such that $(\star)^* M\Phi G = G^*\Phi^* M\Phi G$. For LTI system $G(j\omega)^* = G(-j\omega)^\top$, where $^\top$ means transpose. The standard notation $\mathbf{RH}_\infty$ for stable real rational transfer function is used. A minimal state space realization of the transfer function, $G(j\omega) = C(j\omega I - A)^{-1}B + D$, is given with the shorthand $G \sim \left[\begin{smallmatrix} A & B \\ C & D \end{smallmatrix}\right]$.

## 2. PROBLEM STATEMENT AND PRELIMINARIES

In bilateral teleoperation the main problem is how to ensure that the architecture is going to be stable against all possible human and environment that the design might encounter. As known, the more close assumptions to reality about the uncertainties eventually lead less conservative conditions. In order to use tools that render possible assumptions enriching arranged bilateral architecture, which has been previously analysed by general 2 port network theory approach in Albakri et al. (2013) and by task impedance restriction method in Willaert et al. (2014), will be defined as a classical nominal plant-uncertainty interconnection. Namely, architecture proposed in Fig. 1 will be transformed to interconnection illustrated in Fig. 2.

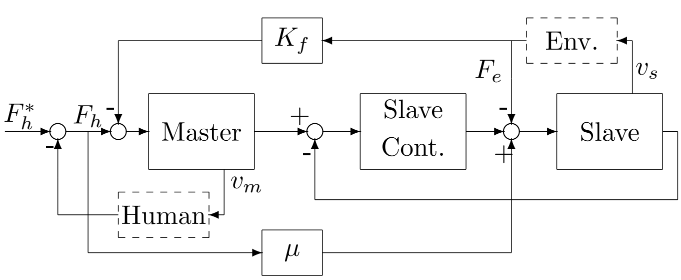


Fig. 1. 3C P-FF bilateral teleoperation architecture. Interconnection will be transformed to a 2C P-F architecture by substituting $\mu = 0$.

A dominated tendency is to define overall teleoperation system as a network. Generally, a two port network can be defined with its Impedance ($\mathbf{R}$), Admittance ($\mathbf{Y}$), or Hybrid ($\mathbf{H}$) matrices (Anderson and Vongpanitlerd, 1973). We will stick to use admittance matrix representation of the bilateral teleoperation proposed as follows,

$$\begin{bmatrix} v_h \\ -v_e \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{bmatrix} F_h \\ F_e \end{bmatrix}$$

where $F_i$, $v_i$ are force and speed of the human and environment, for $i = h, e$, respectively. Negative sign on environmental speed ($v_e$) is required to hold equivalence with network formalism (Adams and Hannaford, 1999). Depicted teleoperation system will be defined as a Lur'e problem; positive interconnection of $G$, a linear system, and $\Delta$, uncertainty within defined class of operators. Here, nominal system will be designated with admittance matrix and $\Delta$ will be structural combination of human and environment, see Fig. 2. Uncertainties will be defined with several quadratic constraints and these definitions will be used with the IQC framework throughout stability analysis.

A general positive feedback interconnection of $G - \Delta$ is defined by

$$\begin{cases} v = f + Gw, \\ w = g + \Delta v, \end{cases}$$

where $g, w, \Delta v \in \mathcal{L}_{2e}^m$ and $Gw, v, f \in \mathcal{L}_{2e}^l$. This feedback interconnection is said to be well-posed if the map $(v, w) \mapsto (g, f)$ has a causal inverse on $\mathcal{L}_{2e}^{m+l}[0,\infty)$. Moreover it is said to be stable if for any $(g, f) \in \mathcal{L}_2^{m+l}$, then $(w, v) \in \mathcal{L}_2^{m+l}$. Absolute stability of the system will be analysed using the IQC framework:

*Definition 1.* (IQC, Megretski and Rantzer (1997)). Let $\Pi : j\mathbb{R} \to C^{(l+m)\times(l+m)}$ be a Hermitian bounded measurable function. Two signals $u \in \mathcal{L}_2^m[0,\infty)$ and $y \in \mathcal{L}_2^l[0,\infty)$ are said to satisfy the IQC defined by $\Pi$, if

$$\int_{-\infty}^{\infty} \begin{bmatrix} \widehat{u}(j\omega) \\ \widehat{y}(j\omega) \end{bmatrix}^* \Pi(j\omega) \begin{bmatrix} \widehat{u}(j\omega) \\ \widehat{y}(j\omega) \end{bmatrix} d\omega \geq 0.$$

Moreover, a bounded system $\Delta : \mathcal{L}_{2e}^m[0,\infty) \to \mathcal{L}_2^l[0,\infty)$ is said to satisfy the IQC defined by $\Pi$ if $u$ and $\Delta u$ satisfy the IQC defined by $\Pi$ for all $u \in \mathcal{L}_2^m$.

*Theorem 1.* (Megretski and Rantzer (1997)). Let $G(s) \in \mathbf{RH}_\infty^{l\times m}$, and $\Delta$ be a bounded causal operator. And we have:

1. for every $\tau \in [0, 1]$, the interconnection of G and $\tau\Delta$ is well-posed,
2. for every $\tau \in [0, 1]$, the IQC defined by $\Pi$ is satisfied by $\tau\Delta$,
3. there exist $\epsilon > 0$ such that

$$\begin{bmatrix} G(j\omega) \\ I \end{bmatrix}^* \Pi(j\omega) \begin{bmatrix} G(j\omega) \\ I \end{bmatrix} \leq -\epsilon I, \quad \forall\omega \in \mathbb{R}.$$

Then, the positive feedback interconnection of $G$ and $\Delta$ is stable.

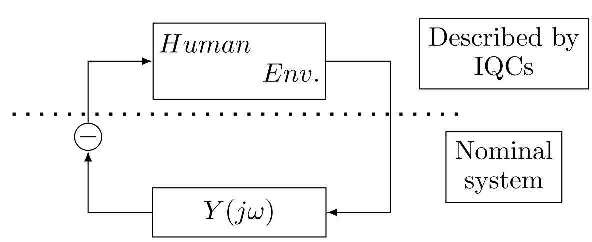


Fig. 2. Delay free bilateral teleoperation system as a Lur'e interconnection.

The human operator will be assumed as a bounded LTI passive system. An LTI system $\Delta \in \mathbf{RH}_\infty$ is said to be passive if $\Delta(j\omega) + \Delta(j\omega)^* \geq 0$ for all $\omega \in \mathbb{R}$. The class of multipliers preserving the positivity of this class is defined by Feron (1997):

*Definition 2.* Let $\lambda$ be a transfer function, then $\lambda$ belongs to the class of passive multipliers $\mathcal{P}$ if $\lambda(\omega) = \lambda(\omega)^*$ and $\lambda(j\omega) > 0$.

*Lemma 2.* Given a bounded LTI passive system $\Delta$ and $\lambda \in \mathcal{P}$, then

$$\int_{-\infty}^{\infty} \begin{bmatrix} \widehat{u}(j\omega) \\ \widehat{\Delta u}(j\omega) \end{bmatrix}^* \begin{bmatrix} 0 & \lambda(\omega) \\ \lambda(\omega) & 0 \end{bmatrix} \begin{bmatrix} \widehat{u}(j\omega) \\ \widehat{\Delta u}(j\omega) \end{bmatrix} d\omega \geq 0. \quad (1)$$

On the other hand, environment is assumed as memoryless, bounded, monotone nonlinear operator. A nonlinearity $\phi : \mathcal{L}_{2e}[0,\infty) \to \mathcal{L}_{2e}[0,\infty)$ is said to be memoryless

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