Control in Robotics
Part 4: Telerobotics

Mohammad Motaharifar

Department of Electrical Engineering
University of Isfahan

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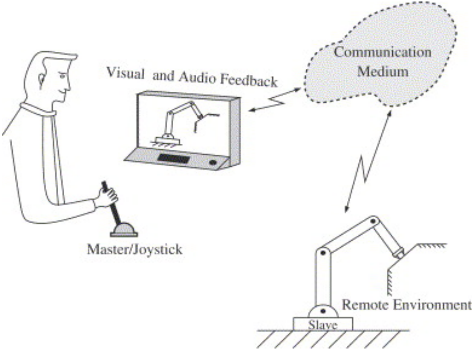
Introduction of Telerobotics

- Telerobotics or teleoperation extends the human capability to manipulating objects remotely by providing the operator with similar conditions as those at the remote location.
- Applications
  - Performing tasks in hazardous environments
  - Remote surgery (Telesurgery)
  - Underwater vehicles (AUVs)
  - Space robotics (Discovery)

Introduction of Telerobotics

- A telerobotics system is achieved via installing the master robot, at the human's end that provides motion commands to the slave which is performing the actual task.
  (Video of Omega/Kuka robot teleoperation system)



Introduction of Telerobotics

- In a general setting, the human imposes a force on the master manipulator which in turn results in a displacement that is transmitted to the slave that mimics that movement.
- If the slave possess force sensors, then it can transmit or reflect back to the master reaction forces from the task being performed, which enters into the input torque of the master, and the teleoperator is said to be controlled bilaterally.
- Although reflecting the encountered forces back to the human operator enables the human to rely on his/her tactile senses along with visual senses, it may cause instability in the system if delays are present in the communication media.
- This delay-induced instability of force reflecting teleoperators has been one of the main challenges faced by researchers.

Introduction of Telerobotics

- The main goals of telerobotics are twofold:
  - Stability: Maintain stability of the closed-loop system irrespective of the behavior of the operator or the environment.
  - Telepresence: Provide the human operator with a sense of telepresence, with the latter regarded as transparency of the system between the environment and the operator.
- These tasks are generally conflicting. However, satisfying these requirements extends the capabilities of the human by scaling her/his power into manipulating huge objects, as in outer space construction, or performing delicate tasks, as in microsurgery; thus projecting his/her expertise into distant locations.

Haptic technology

- Haptic technology refers to any technology that can create an experience of touch by applying forces, vibrations, or motions to the user.
- These technologies can be used to create virtual objects in a computer simulation, to control virtual objects, and to enhance remote control of machines and devices (telerobotics).
- Haptic systems extend the abilities of human operators to interact with real or virtual, local or remote environments.
- Owing to this feature, haptic technology has received significant interest in applications such as medical simulations, computer-aided design, outer space, handling poisonous materials, etc.

Medical applications

Long-term objective: Develop new technologies that reduce the burden on the healthcare system by making interventions

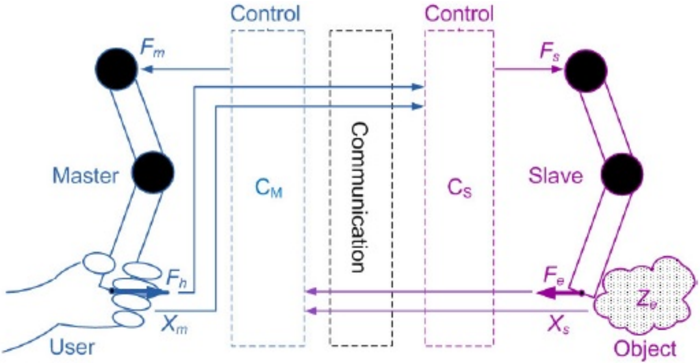
- less traumatic (i.e., faster recovery and shorter hospital stay)
- more efficient (i.e., better accuracy and reliability)
- available to remote areas

(Video of da Vinci Robotic Surgery)

(Video of PRECEYES Surgical System)

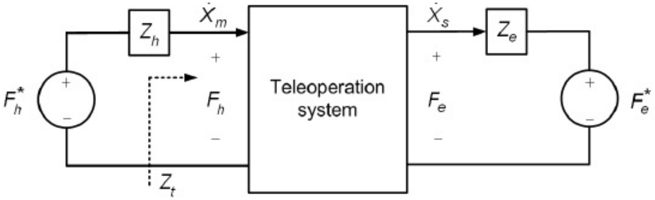
Modelling a Telerobotic System

- An important approach is to model a teleoperation system as a two-port network. We illustrate such modelling for a linear system using hybrid parameters.



Modelling a Telerobotic System

- By considering velocities and forces in a teleoperation system as currents and voltages, an equivalent circuit representation of the system can be obtained:



- $Z_h(s)$ and $Z_e(s)$ are dynamic characteristics of the human operator's hand and the remote environment, respectively.
- F_h^* and F_e^* are respectively the operator's and the environment's exogenous input forces and are independent of teleoperation system behaviour.

Modelling a Telerobotic System

- It is generally assumed that the environment is passive ($F_e^* = 0$), and that the operator is passive in the sense that he/she does not perform actions that will make the teleoperation system unstable.
- The teleoperation system, which does not include the human operator or the environment, can be modeled as a two-port network:

$$\begin{bmatrix} F_h \\ -\dot{X}_s \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} \dot{X}_m \\ F_e \end{bmatrix}$$

Modelling a Telerobotic System

Question: What is the physical meaning of the elements of the hybrid matrix?

$$\begin{bmatrix} F_h \\ -\dot{X}_s \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} \dot{X}_m \\ F_e \end{bmatrix}$$

performance metrics

- Free-motion input impedance $\quad h_{11} = F_h/\dot{x}_m|_{F_e=0} \quad$ 0
- Locked-master force tracking $\quad h_{12} = F_h/F_e|_{\dot{x}_m=0} \quad$ -1
- Free-motion position tracking $\quad h_{21} = -\dot{x}_s/\dot{x}_m|_{F_e=0} \quad$ 1
- Locked-master output admittance $\quad h_{12} = -\dot{x}_s/F_e|_{\dot{x}_m=0} \quad$ 0

Modelling a Telerobotic System

- We want the user to feel as he/she is directly interacting with the object.
- This is called transparency, and requires matching of positions and forces on the two sides.
- Transparency Conditions $\begin{cases} F_h = F_e \\ X_m = X_s \end{cases}$
- Equivalently $Z_t = Z_e$ where $Z_t = F_h/X_m, Z_e = F_e/X_s$
- Ideal transparency means

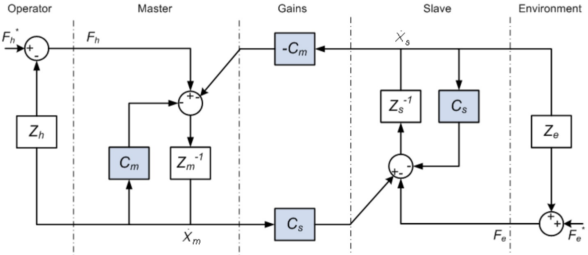
$$H_{\text{ideal}} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \quad (1)$$

Architectures of Telerobotic systems

- For achieving the ideal response (28), various teleoperation control architectures are proposed in the literature.
- These control architectures are usually classiffed as position-force (i.e. position control at the master side and force control at the slave side), force-position, position-position, and force-force architectures.
- We are interested in those in which the slave is under position control, namely position-position and force-position.
- A more general classiffication is by the number of communication channels required for transmitting position and force values from the master to the slave and vice versa in each bilateral control architecture.
- In the following, we present the above-mentioned two-channel architectures in addition to a more sophisticated four-channel and three channel architecture.

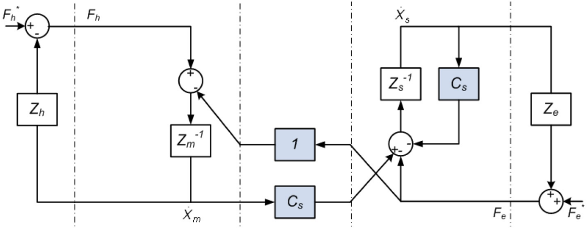
Position Error Based (PEB)

- A position-error based is also called position-position architecture.
- It does not use any force sensor measurements and merely tries to minimize the difference between the master and the slave positions, thus reflecting a force proportional to this difference to the user once the slave makes contact with an object.



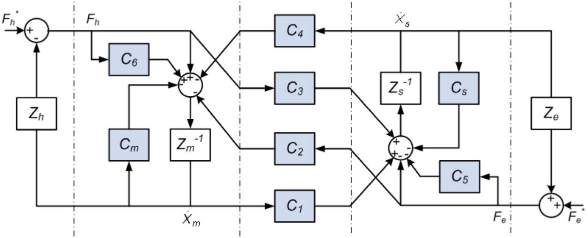
Direct Force Reflection (DFR)

- It is also called force-position architecture.
- This method requires a force sensor to measure the interactions between the slave and the environment.
- While the DFR method proves to be better than the PEB method, both methods suffer from the less-than-ideal transparency.



4-channel architecture

- A general 4-channel (4CH) bilateral teleoperation architecture is depicted here.
- This architecture can represent other teleoperation structures through appropriate selection of subsystem dynamics C_1 to C_6.
- The compensators C_5 and C_6 constitute local force feedback at the slave side and the master side, respectively.



4-channel architecture

- The H-parameters for the 4CH architecture are:

$$\begin{aligned} h_{11} &= (Z_{ts}Z_{tm} + C_1 C_4)/D \\ h_{12} &= \big(Z_{ts}C_2 - (1 + C_5)C_4\big)/D \\ h_{21} &= -\big(Z_{tm}C_3 + (1 + C_6)C_1\big)/D \\ h_{22} &= -\big(C_2 C_3 - (1 + C_5)(1 + C_6)\big)/D \end{aligned} \tag{2}$$

  where $Z_{tm} = Z_m + C_m$, $Z_{ts} = Z_s + C_s$, and
  $D = -C_3 C_4 + Z_{ts}(1 + C_6)$.

- In contrast to the 2-channel (2CH) architectures, a sufficient number of parameters in the 4CH architecture enables it to achieve ideal transparency.In fact, by selecting

$$\begin{aligned} C_1 &= Z_{ts}, \qquad C_2 = 1 + C_6 \\ C_3 &= 1 + C_5, \quad C_4 = -Z_{tm} \end{aligned} \tag{3}$$

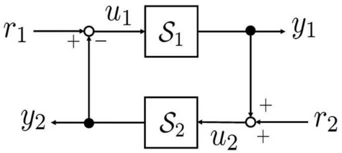
  the ideal transparency conditions are fully met.

3-channel architecture

- Another potential benefit of the general 4CH architecture is that by proper adjustment of the local feedback parameters, it is possible to obtain two classes of 3-channel (3CH) control architectures, which can be transparent under ideal conditions.
- The first class of 3CH architectures is derived by setting C2 = 1 and C3 = 0. As a consequence, C5 = -1 and C6 = 0. In other words, there is no need for master/operator interaction force measurement and therefore, the number of sensors in the system can be reduced.
- The second class of 3CH architectures is obtained by setting C2 = 0 and C3 = 1. In this class, force measurement at the slave side is not needed.
- The need for fewer sensors without imposing additional expense on system transparency makes the 3CH architectures extremely attractive from the implementation point of view.

Small Gain Theorem

- Consider the following system



- Let γ_1 and γ_2 be the gains of operators S_1 and S_2.
- The gain of an operator is defined as: $\gamma_i = \sup_{u_i} \frac{\|S_i u_i\|}{\|u_i\|}$
- Closed loop system is BIBO stable if $\gamma_1\gamma_2 < 1$ and its gain is also smaller than:

$$\gamma = \frac{\gamma_1}{1 - \gamma_1\gamma_2}$$

Passivity

- Passivity theory, which applies equally well to linear and non-linear systems, is a powerful method to analyze stability of teleroboticn systems.
- It can be introduced in terms of the energy of a single-port network

$$E(t_0) + \int_{t_0}^{t} v(\tau)i(\tau)d\tau \geq 0$$

- To give a formal definition, the inner product of two vectors is given by:

$$< x, y >= \int_{0}^{\infty} x^T(\tau)y(\tau)d\tau$$

- The mapping H is said to be passive if $< Hx, x > \geq \beta, \beta \in \mathbb{R}$
- A passive system/component either consumes (but does not produce) energy (e.g., a damper or a resistor) or neither consumes nor produces energy (e.g., a spring or a capacitor).

Stability of a telerobotic system

- In a bilateral telerobotic system, the feedback loop of the system includes both the environment and the human operator. The stability of the whole system does therefore depend on both the teleoperator (modeled by the impedance Z_h) and the environment (modeled by the impedance Z_e).
- Often, the numerical values of Z_h and Z_e are not known.
- A first set of stability measures can be used when Z_h and Z_e are not known exactly, but it is known that they fulfil passivity property. We will call this *absolute stability*.
- A second set of stability measures can be used when Z_h and Z_e are known. We will call this *closed-loop stability*.
- The first set is a stricter requirement for the teleoperator, because it guarantees that the teleoperator is stable in contact with a larger range of impedances.

Stability of a telerobotic system

- Absolute stability means that the system is stable for all possible passive operators and environments.
- Most physical environments are passive For instance, a sponge is passive but a beating heart is not passive.
- It is generally assumed that the human operator is passive in the sense that the operator does not perform actions to make the system unstable.
- The necessary and sufficient conditions for absolute stability can be expressed in terms of the H matrix elements and the real parts thereof, as seen in the next slide.

Stability of a telerobotic system

Theorem (Llewellyns theorem)

A telerobotic system with the hybrid matrix

$$\begin{bmatrix} F_h \\ -\dot{X}_s \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} \dot{X}_m \\ F_e \end{bmatrix}$$

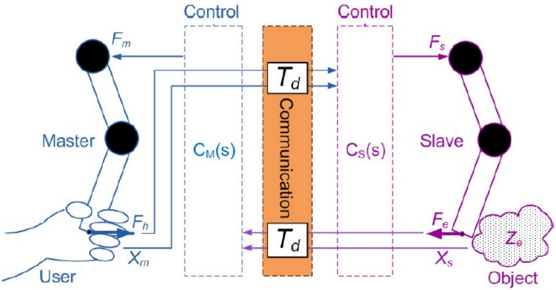
is absolutely stable if and only if: (a) $h_{11}(s)$ *and* $h_{22}(s)$ *have no poles in the right half plane (RHP); (b) any poles of* $h_{11}(s)$ *and* $h_{22}(s)$ *on the imaginary axis are simple with real and positive residues; and (c) for* $s = j\omega$ *and any values of* ω

$$\mathcal{R}(h_{11}) \geq 0, \qquad \mathcal{R}(h_{22}) \geq 0,$$
$$2\mathcal{R}(h_{11})\mathcal{R}(h_{22}) - \mathcal{R}(h_{12}h_{21}) - |(h_{12}h_{21}| \geq 0$$

where $\mathcal{R}(.)$ *and* $|.|$ *denote the real and absolute values.*

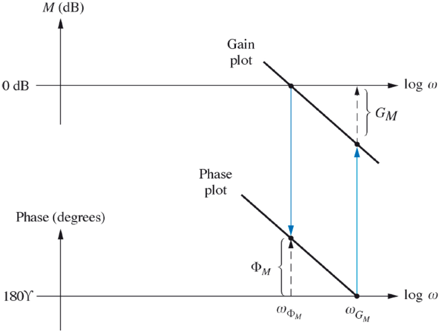
Telerobotics under delay

- There are communication delays due to large distances between the mater and the slave.
- We know that delay in any control system causes instability and a telerobotic system is no exception.



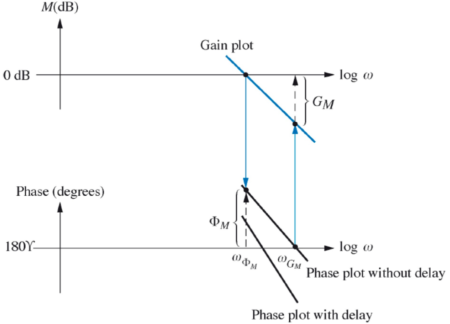
Telerobotics under delay

- Reminder: Gain and phase margins
  - ω_{GM} - Phase crossover frequency: Frequency when phase angle is 180
  - G_M - Gain Margin: Gain at ω_{GM}
  - $\omega_{\phi M}$ - Gain crossover frequency: Frequency when gain is 0
  - ϕ_M - Phase Margin: Difference between the phase at $\omega_{\phi M}$ and 180



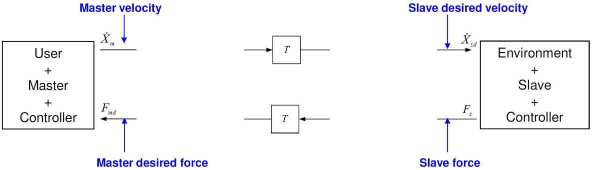
Telerobotics under delay

- The magnitude plot and the gain crossover frequency ($\omega_{\phi M}$) are unaffected by time delay.
- Since $\omega_{\phi M}$ is unaffected by delay, the phase margin is reduced, moving the system closer to instability.
- The phase crossover frequency (ω_{GM}) is reduced under delay, thus reducing the gain margin and moving the system closer to instability



Telerobotics under delay

- Why does a telerobotic system get unstable under time delay?



- Objectives of a telerobotic system: $\begin{cases} \dot{X}_{md}(t) = \dot{X}_s(t - T_d) \\ F_{md}(t) = F_s(t - T_d) \end{cases}$
- Communication channel hybrid matrix

$$H_{\text{ideal}} = \begin{bmatrix} 0 & e^{-sT_d} \\ -e^{-sT_d} & 0 \end{bmatrix}$$

- Using Llewellyns theorem, it can be shown that the above-mentioned hybrid matrix for the case of time delay is not absolutely stable. The physical meaning of this is that the delayed channel generates energy (non-passive behavior).

Nonlinear Telerobotics

- The majority of the existing control structures for telerobotic systems have been designed for linear model of the system or have not reported any stability analysis for the nonlinear case.
- A few existing control structures for telerobotic systems have reported nonlinear stability analysis based on:
    - Passivity approach
    - ISS approach and small gain theorem

Passive bilateral telerobotics

- Prominent among the works on nonlinear telerobotics are the ones that exploit the basic property of passivity of the teleoperators, that are referred here as passivity-based controllers.
- These schemes, which include scattering-based, damping injection and adaptive controllers, have been developed invoking various analysis and design tools, which complicates their comparison and relative performance assessment.
- In [Nuno, 2011], a unified framework is proposed for the analysis of such controllers, providing a general Lyapunov-like function that can be tailored to fit different control schemes designed to deal with constant or variable time-delays, with or without the scattering transformation and with or without position tracking.

Passive bilateral telerobotics

- Model of the Telerobotic system

$$\begin{aligned} M_l(q_l)\ddot{q}_l + C_l(q_l, \dot{q}_l)\dot{q}_l + g_l(q_l) &= \tau_h - \tau_l^* \\ M_r(q_r)\ddot{q}_r + C_r(q_r, \dot{q}_r)\dot{q}_r + g_r(q_r) &= \tau_r^* - \tau_e \end{aligned} \qquad (4)$$

- General assumptions:
  - Passivity of the human operator and the environment: $\exists \kappa_l, \kappa_r \in \mathbb{R}_{\geq 0}$, s. t. $E_h := -\int_0^t \dot{q}_l \tau_h d\sigma + \kappa_l \geq 0$ and $E_e := -\int_0^t \dot{q}_r \tau_e d\sigma + \kappa_r \geq 0$
  - Pre-compensation of the gravitational torques: $(\tau_i^* = \tau_i - g_i(q_i))$
- Assumptions on time delay:
  - Boundedness: $0 \geq T_i(t) \geq *T_i < \infty$
  - Not growing or decreasing faster than time itself, $|\dot{T}_i| < 1$

Passive bilateral telerobotics

- A general Lyapunov-like function intended to unify the stability analysis of different controllers:

$$V(q_i, \dot{q}_i, t) = V_1(q_i, \dot{q}_i) + V_2(t) + V_3(q_i, t) \qquad (5)$$

- V_1 is a weighted sum of the kinetic energy of the local and remote manipulators:

$$V_1 = \frac{\beta_l}{2} \dot{q}_l^T M_l(q_l) \dot{q}_l + \frac{\beta_r}{2} \dot{q}_r^T M_r(q_r) \dot{q}_r \qquad (6)$$

- V_2 is the weighted sum of the energies supplied (or extracted) by the human and the environment:

$$V_2 = \beta_l E_h + \beta_r E_e \qquad (7)$$

- Notably, $\dot{V}_1 + \dot{V}_2 = -\beta_l \dot{q}_l \tau_l + \beta_r \dot{q}_r \tau_r$
- V_3 is determined by the controller, that establishes the coupling between the local and remote manipulators.

Passive bilateral telerobotics

- P-like Controller (P+d)

$$\begin{aligned} \tau_l &= K_l[q_r(t - T_r(t)) - q_l] - B_l\dot{q}_l \\ \tau_r &= K_r[q_r - q_l(t - T_l(t))] + B_r\dot{q}_r \end{aligned} \tag{8}$$

- Set the controllers gain such that

$$4B_lB_r > (*T_l^2 + *T_r^2)K_lK_r \tag{9}$$

- Then, we have
  - I. Velocities and position error are bounded, i.e. $\{\dot{q}_i, q_l - q_r, q_l - q_r(t - T_r(t))\} \in L_\infty$, and
  - II. If $\tau_h = \tau_e = 0$, then $|q_l - q_r(t - T_r(t))| \to 0, t \to \infty$

Passive bilateral telerobotics

- Proof: The following Lyapunov function is considered

$$V = \frac{1}{2}\dot{q}_l^T M_l(q_l)\dot{q}_l + \frac{K_l}{2K_r}\dot{q}_r^T M_r(q_r)\dot{q}_r + \frac{K_l}{2}|q_l - q_r|^2 + \int_0^t (\dot{q}_l^T \tau_h - \frac{K_l}{K_r}\dot{q}_r^T \tau_e) d\sigma + \kappa_l + \frac{K_l}{K_r}\kappa_r \quad (10)$$

- Then, we have

$$\dot{V} = -B_l|\dot{q}_l|^2 - \frac{K_l B_r}{K_r}|\dot{q}_r|^2 - K_l\dot{q}_l^T \int_{-T_r(t)}^{0} \dot{q}_r(t+\theta)d\theta - K_l\dot{q}_r^T \int_{-T_l(t)}^{0} \dot{q}_l(t+\theta)d\theta \quad (11)$$

- Integrating from 0 to t and after some calculation, we can prove the theorem.

Passive bilateral telerobotics

- PD-like Controller (PD+d)

$$\tau_l = K_d[\gamma_r \dot{q}_r(t - T_r(t)) - \dot{q}_l] + K_l[q_r(t - T_r(t)) - q_l] - B_l \dot{q}_l$$
$$\tau_r = K_d[\dot{q}_r - \gamma_l \dot{q}_l(t - T_l(t))] + K_r[q_r - q_l(t - T_l(t))] + B_r \dot{q}_r \quad (12)$$

where $\gamma_i^2 = 1 - \dot{T}_i(t)$

- Proof of boundedness is similar to the P-like approach.
- PD+d controllers are sensitive to abrupt changes in time delays. This is due to the inclusion of variable gain $\gamma_i(t)$ [Nuno, 2011]

Passive bilateral telerobotics

- A special case of the PD + d controllers, with only the D action, are the passive output interconnection schemes, which simply interconnect the delayed passive outputs $\dot{q}_i$ of the local and remote manipulators .
- The main motivation for using these schemes is their delay-independent stability property.
- By using D controllers, we can only prove asymptotic convergence of velocity errors to zero. However, if damping injection is added, resulting D+d controller, it yields asymptotic convergence of velocities to zero.

ISS approach

- Two special classes of comparison functions known as class $\mathcal{K}$ and class $\mathcal{KL}$ are very useful in the definition of ISS.
- Definition: A continuous function $\alpha : [0, a) \to [0, \infty)$ is said to belong to class $\mathcal{K}$ if it is strictly increasing and $\alpha(0) = 0$. t is said to belong to class $\mathcal{K}_\infty$ if $a = \infty$ and $\alpha(r) \to \infty$ as $r \to \infty$.
- Definition: A continuous function $\beta : [0, a) \times [0, \infty) \to [0, \infty)$ is said to belong to class $\mathcal{KL}$ if, for each fixed s, the mapping $\beta(r, s)$ belong to class $\mathcal{K}$ w.r.t. r and, for each fixed r , the mapping $\beta(r, s)$ is decreasing w.r.t. s and $\beta(r, s) \to 0$ as $s \to \infty$.

ISS approach

- *Definition of ISS Stability:* The general form of a dynamic system is considered as

$$\dot{x} = f(t, x, u) \tag{13}$$

where $f : [0, \infty) \times \mathbb{R}^n \times \mathbb{R}^m \to \mathbb{R}^n$ is a piecewise continuous function in t and locally Lipschitz in x and u. The system (13) is ISS if there exists a class $\mathcal{KL}$ function β and a class $\mathcal{K}$ function γ such that for any initial state x_0 and any bounded input the following inequality is satisfied:

$$\|x(t)\| \leq \beta(\|x_0\|, t) + \gamma(\sup \|u(t)\|), \qquad 0 \leq t \leq T. \tag{14}$$

ISS approach

Theorem

Consider that there exists a continuously differentiable function $V : [0, \infty) \times \mathbb{R}^n \to \mathbb{R}$ such that

$$\alpha_1(\|x\|) \leq V(x) \leq \alpha_2(\|x\|)$$
$$\dot{V}(x) \leq -W(x), \qquad \forall \|x\| \geq \rho(\|u\|) > 0$$

where $\dot{V}$ is the derivative of V along the trajectory solutions of the system (13), α_1 and α_2 are class $\mathcal{K}_\infty$ functions, ρ is class $\mathcal{K}$ function, and $W(x)$ is a positive definite function on $\mathbb{R}^n$. Then, the system (13) is ISS with $\gamma = \alpha_1^{-1} \circ \alpha_2 \circ \rho$.

ISS approach

- In [Polushin, 2003], a control scheme is proposed which makes the teleoperator system input-to-state stable regardless of the delay in the communication channel.
- The dynamics of the bilateral control system are described as

$$H_m(q_m)\ddot{q}_m + C_m(q_m, \dot{q}_m)\dot{q}_m + G_m(q_m) = F_h + u_m \qquad (15)$$

$$H_s(q_s)\ddot{q}_s + C_s(q_s, \dot{q}_s)\dot{q}_s + G_s(q_s) = F_e + u_s \qquad (16)$$

- The control law is

$$\begin{aligned} u_m = {} & -H_m(q_m)\Lambda_m\dot{q}_m - C_m(q_m, \dot{q}_m)\Lambda_m q_m \\ & + G_m(q_m) - K_m(\dot{q}_m + \Lambda_m q_m) + \hat{F}_e \qquad (17) \end{aligned}$$

$$\begin{aligned} u_s = {} & H_s(q_s)\Lambda_s(\hat{\dot{q}}_m - \dot{q}_s) + C_s(q_s, \dot{q}_s)\Lambda_s(\hat{q}_m - q_s) \\ & + G_s(q_s) - K_s(\dot{q}_s + \Lambda_s(q_s - \hat{q}_m)) \qquad (18) \end{aligned}$$

ISS approach

Theorem

For any communication delay, the controlled bilateral teleoperator system is input to state stable with respect to the input $(F_h^T, F_e^t)^T$.

- *Proof*: The following Lyapunov function is considered for the master system

$$V(q_m, e_m) = \frac{1}{2} e_m^T H_m(q_m) e_m + \varepsilon_0 q_m^T P_m q_m \tag{19}$$

where $e_m = \dot{q}_m + \Lambda_m q_m$

- We can find c_1, c_2 such that

$$v_1(|e_m|^2 + |q_m|^2) \leq V(q_m, e_m) \leq v_1(|e_m|^2 + |q_m|^2) \tag{20}$$

ISS approach

- After some calculation, we have the following equation which shows the ISS stability

$$\dot{V}_m \leq -\frac{\lambda_{\min}(K_m)}{2}|e_m|^2 - \frac{\lambda_{\min}(K_m)}{16|P|^2}|q|^2 + \frac{1}{\lambda_{\min}(K_m)}|F_h - \tilde{F}_e|^2 \quad (21)$$

- Proof of ISS stability for the slave subsystem is similar.

Multi-User Telerobotics

- Examples multiple user teleoperation systems: robotic rehabilitation and surgical training.
- The challenge of controller design for such systems is to *m*imic or enhance the conditions of manual collaboration, which is to transfer the true feel of performing a task during guidance and also to enable the trainer or the system to naturally transfer task authority to the trainee in due time (or to block authority in case of a sudden mistake by the trainee).
- One way to assess the performance of control architectures in transferring the true feel of performing tasks in teleoperation and haptic systems is through transparency analysis, or through the assessment of the impedance transferred to each user.

Multi-User Telerobotics

- For single-user systems, this impedance should match a reference impedance, which is the environment impedance.
- In dual-user or multiuser systems, the transmitted impedance is also expected to be affected by the dynamics of other users. As such, new kinesthetic performance measures and performance references should be identified and evaluated.
- Recently, there have been a number of control architectures proposed for multimaster/multislave teleoperation or haptic systems.

Multi-User Telerobotics

- A multilateral control architecture has been proposed in [Khademian, 2012] for direct interaction between two users as well as between the users and the environment through two masters and one slave.
- In this architecture, both positions and forces of the masters and the slave are exchanged among the three robots, thus creating a six-channel multilateral shared control architecture that provides kinesthetic feedback from the environment.

Multi-User Telerobotics

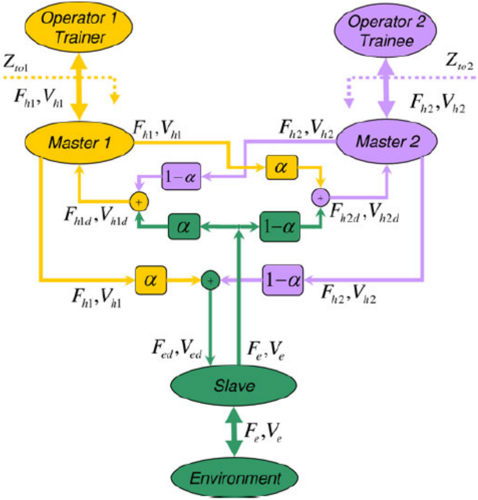


Figure : Six-channel multilateral shared control architecture.

Multi-User Telerobotics

- The challenge of the design of multiuser teleoperation and haptic control systems is to mimic or enhance the condition of manual collaboration.
- In manual training systems, for example, the trainee not only feels the dynamics of the environment through the tool but also the dynamics of the trainer.
- Therefore, the impedance felt is a mix of impedances and as such, to convey that feel, a weighted sum of positions and forces should logically be feedback to each user.
- To this purpose, the shared control architecture, the masters and the slave are interconnected and the desired position and force commands are shared between the positions and forces of the other two robots.

Multi-User Telerobotics

- Therefore, we should have

$$\begin{aligned} V_{h1d} &= \alpha V_e + (1-\alpha) V_{h2} \\ V_{h2d} &= (1-\alpha) V_e + \alpha V_{h1} \\ V_{ed} &= \alpha V_{h1} + (1-\alpha) V_{h2} \end{aligned}$$

and

$$\begin{aligned} F_{h1d} &= \alpha F_e + (1-\alpha) F_{h2} \\ F_{h2d} &= (1-\alpha) F_e + \alpha F_{h1} \\ F_{ed} &= \alpha F_{h1} + (1-\alpha) F_{h2} \end{aligned}$$

Multi-User Telerobotics

- The aforementioned dual-user teleoperation control architecture is designed for training purposes so that one user (trainer) can affect the other users (trainees) movement through the haptic devices.
- Training mode($\alpha = 1$): In this case, master 1 and environment form a four-channel bilateral teleoperation system and the master 1 position acts as an exogenous input for the master 2 closed-loop dynamics. This way, the motion of master 2 is fully controlled by master 1, and thus, operator 2 is dragged by operator 1.

Multi-User Telerobotics

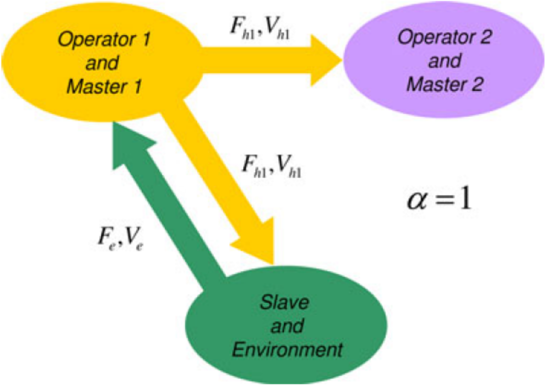


Figure : Training mode ($\alpha = 1$). Master 1 and slave form a four-channel bilateral architecture and operator 2 only receives commands.

Multi-User Telerobotics

- Evaluation mode ($\alpha = 0$): Dual to the ($\alpha = 1$) case, the trainee (master 2) has full control over the task trainer (master 1), which is suitable for evaluating the trainees performance.
- Guidance mode ($0 < \alpha < 1$): Both users can control the slave, and the trainer can guide the trainee to collaboratively perform a task in a shared environment.
- In the shared architecture, the dominance factor is changed progressively and manually. The dominance factor should ultimately be set automatically according to the quantified level of skill of the users. Quantification of the users skills is an active area of research.

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