PHYSICAL HUMAN-ROBOT INTERACTION

Two-port Representation

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Outline

Force feedback

Two-port Representation

When does a Teleoperation System work well?

Force feedback

Force feedback

Communicate contact force information from the slave to the master in order to kinesthetically couple the operator to the environment

- increase the sense of *telepresence*
- improve *task performance*

How to measure/estimate interactions forces/torques?

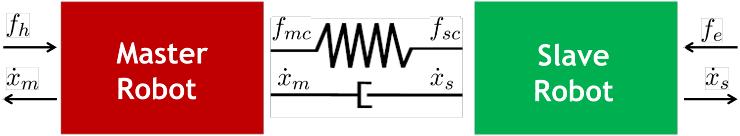
REMARK. without local force feedback, robots with high-gear ratios are insensitive to changes in the interaction force.

1. By embedding force/torque sensors at the end-effector of the robot

2. By deriving the force/torque from motor currents (e.g. Barrett WAM)

Force feedback

3. By relating the position displacement between master and slave to a force/torque (e.g. spring-damper coupling)



$$
\begin{aligned}
f_{mc} &= -K(x_m - x_s) - B(\dot{x}_m - \dot{x}_s) \\
f_{sc} &= K(x_m - x_s) + B(\dot{x}_m - \dot{x}_s)
\end{aligned}
$$

Useful solution when high-gear ratios are needed to provide high torque/force but the integration of force sensors at the end-effectors is physically (or economically) impossible (e.g. disposable surgical tools)

Transfer functions

Let's start with SISO linear systems: it is possible to derive the transfer function for each subsystems

In particular, we will focus on the transfer function relating speed and force (i.e. impedance Z or admittance $A = Z^{-1}$)

$$\begin{aligned} Z &= \frac{f}{\dot{x}} \left(= \frac{f}{v} \right) \\ A = Z^{-1} &= \frac{\dot{x}}{f} \left(= \frac{v}{f} \right) \end{aligned}$$

Time-Domain models

Human	$m_h\ddot{x}_h + b_h\dot{x}_h + c_h x_h = f_h^\star - f_h$
Master robot	$m_m\ddot{x}_m + b_m\dot{x}_m + k_m x_m = f_{mc} + f_h$
Slave robot	$m_s\ddot{x}_s + b_s\dot{x}_s + k_s x_s = f_{sc} - f_e$
Environment	$m_e\ddot{x}_e + b_e\dot{x}_e + c_e x_e = f_e$

al denominatore voglio la velocità

sX(s) è la velocità in laplace (i.e. il laplace di $\dot{x}(t)$)

$\mathcal{L}(\dot{x}(t)) = sX(s)$

Human $$Z_h(s) = \frac{F_h^\star(s) - F_h(s)}{sX_h(s)} = \frac{m_h s^2 + b_h s + k_h}{s}$$

Master robot $$Z_m^{-1}(s) = \frac{sX_m(s)}{F_{mc}(s) + F_h(s)} = \frac{s}{m_m s^2 + b_m s + k_m}$$

Slave robot $$Z_s^{-1}(s) = \frac{sX_s(s)}{F_{sc}(s) - F_e(s)} = \frac{s}{m_s s^2 + b_s s + k_s}$$

Environment $$Z_e(s) = \frac{F_e(s) - F_e^\star(s)}{sX_e(s)} = \begin{cases} \frac{m_e s^2 + b_e s + k_e}{s}, & \text{contact} \\ 0, & \text{free motion} \end{cases}$$

Coupled Transfer Functions

Master side: Human + Master robot ($x_h(t) = x_m(t)$, $X_h(s) = X_m(s)$)

$$Z_{mh} := Z_m(s) + Z_h(s) = \frac{F_{mc}(s) + F_h^\star(s)}{sX_m(s)} = \frac{(m_s + m_h)s^2 + (b_s + b_h)s + (k_s + k_h)}{s}$$

m_h

Coupled Transfer Functions

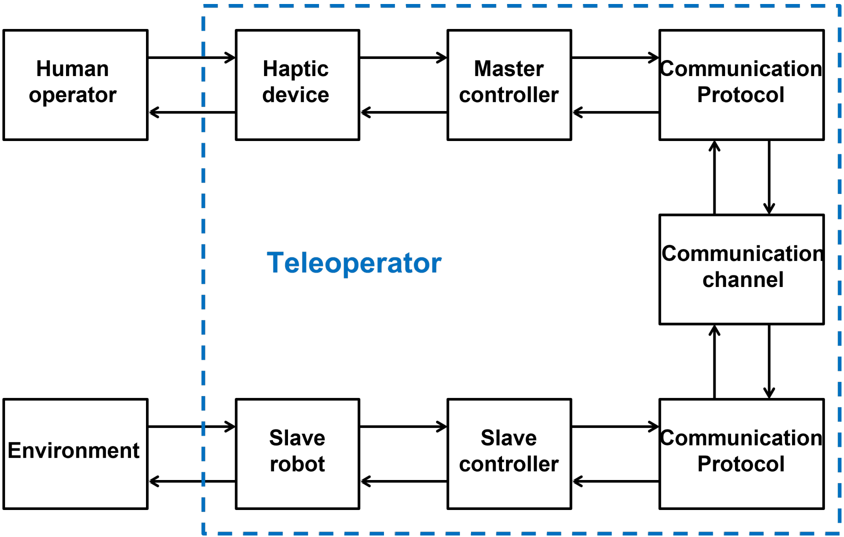
Slave side: Environment + Slave robot ($x_e(t) = x_s(t)$, $X_e(s) = X_s(s)$)

$$Z_{se} := Z_s(s) + Z_e(s) = \frac{F_{sc}(s) - \sigma F_e^\star(s)}{sX_s(s)} = \frac{(m_s + \sigma m_e)s^2 + (b_s + \sigma b_e)s + (k_s + \sigma k_e)}{s}$$

where $\sigma = \begin{cases} 1, & \text{contact} \\ 0, & \text{free motion} \end{cases}$

Two-port Representation

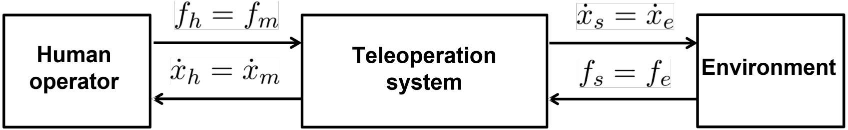
Two-port Representation



Two-port Representation

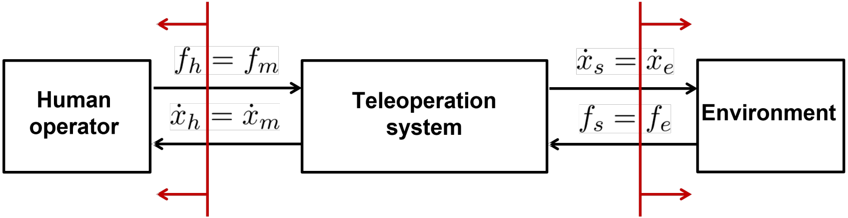
Each block interacts with the others through *energetic ports*, i.e. through *effort-flow pairs*

- Efforts: $f_h = f_m$, $f_e = f_s$
- Flows: $\dot{x}_h = \dot{x}_m$, $\dot{x}_s = \dot{x}_e$



The behavior of the teleoperation system is completely characterized by the effort and flow at the two ports.

Of these four variables, two may be chosen as independent, and the remaining two are dependent



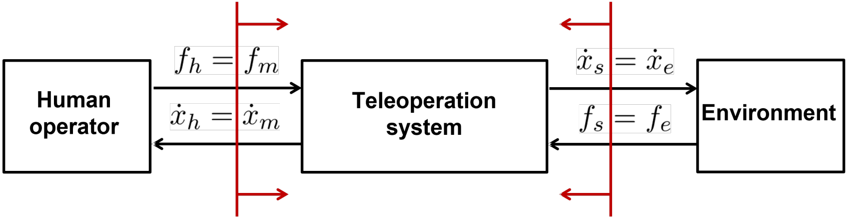
(without considering the exogenous forces)

$$Z_h(s) = \frac{F_h(s)}{sX_h(s)} = \frac{F_h(s)}{sX_m(s)}, \qquad Z_e(s) = \frac{F_e(s)}{sX_e(s)} = \frac{F_e(s)}{sX_s(s)}$$

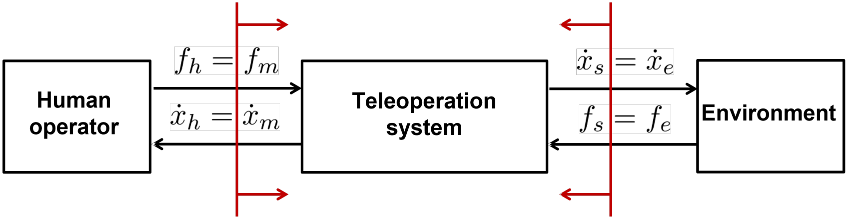
with abuse of notation (mixing time and frequency notation)

$$f_h = Z_h(s)\dot{x}_m, \qquad f_e = Z_e(s)\dot{x}_s$$

Two-port Representation: *Inward*



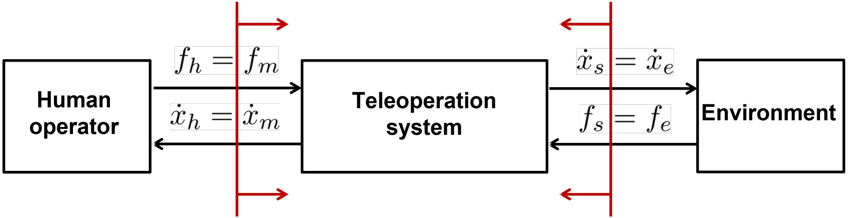
Master robot
Master controller
Communication channel
Slave controller
Slave robot



Impedance matrix (i.e. impedance causality)

$$\underbrace{\begin{bmatrix} f_m \\ f_s \end{bmatrix}}_{\text{dip. var}} = \begin{bmatrix} Z_{11}(s) & Z_{12}(s) \\ Z_{21}(s) & Z_{22}(s) \end{bmatrix} \underbrace{\begin{bmatrix} \dot{x}_m \\ \dot{x}_s \end{bmatrix}}_{\text{indep var.}}$$

the impedance matrix maps velocity into force



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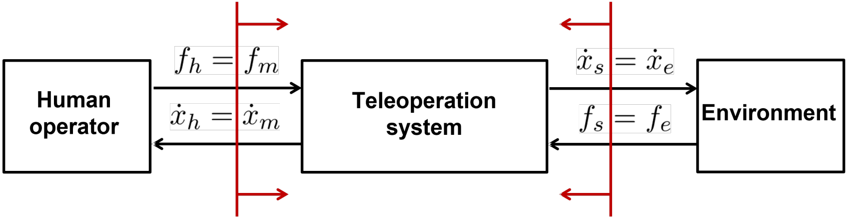
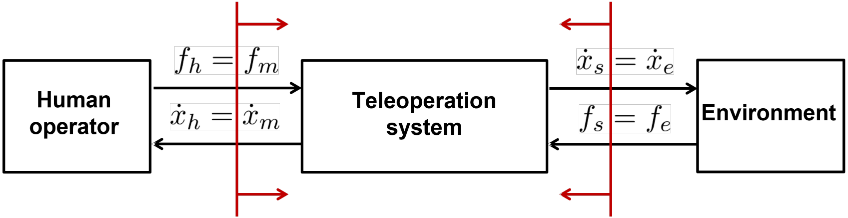
Admittance matrix (i.e. admittance causality)

$$\begin{bmatrix} \dot{x}_m \\ \dot{x}_s \end{bmatrix} = \begin{bmatrix} Y_{11}(s) & Y_{12}(s) \\ Y_{21}(s) & Y_{22}(s) \end{bmatrix} \begin{bmatrix} f_m \\ f_s \end{bmatrix}$$



Hybrid matrix (à la Hannaford)

$$\begin{bmatrix} f_m \\ \dot{x}_m \end{bmatrix} = \begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} \begin{bmatrix} \dot{x}_s \\ -f_s \end{bmatrix}$$



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$$\begin{bmatrix} f_m \\ -\dot{x}_s \end{bmatrix} = \begin{bmatrix} \bar{H}_{11}(s) & \bar{H}_{12}(s) \\ \bar{H}_{21}(s) & \bar{H}_{22}(s) \end{bmatrix} \begin{bmatrix} \dot{x}_m \\ f_s \end{bmatrix}$$

Two-port Representation: *Meaning of H_{ij}*

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Meaning of the transfer functions within the matrix $\bar{H}(s)$:

- $\bar{H}_{11}(s)$ *unconstrained movement impedance*: the equivalent inertia and damping that the operator feels moving the master robot if the slave is in free motion. It should be as low as possible.

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- $\bar{H}_{12}(s)$ *tracking of forces in contact tasks* when the operator keeps the master steady against the forces that the slave encounters. It should tend to unity, if no force scaling is desired, with infinite bandwidth.

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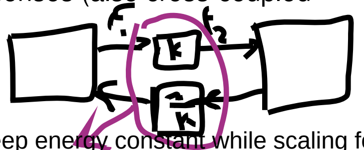
- $\bar{H}_{12}(s)$ *tracking of forces in contact tasks* when the operator keeps the master steady against the forces that the slave encounters. It should tend to unity, if no force scaling is desired, with infinite bandwidth.
- $\bar{H}_{22}(s)$ *contact admittance*: position tracking during contact tasks. we want this as low as possible

When does a Teleoperation System work well?

- **Stability**: broadly speaking, stability implies that all the variables within the teleoperation systems are bounded.
- **Transparency**: a teleoperated system is transparent if the operator at the master side has the feeling to interact directly with the remote environment at the slave side.
- **Telepresence** denotes a dynamic behavior in which the environmental effects experienced by the slave are transferred through the master to the human without alteration.
  - ★ The operator feels that she/he is “there” without “being” there.
- **Telefunctioning**: the slave forces are functions of the master forces so the human senses forces different from those which the slave senses (also cross-coupled forces); the same for the positioning.
  - ★ Scaling up/down forces or positions/velocities.

$f_2 = k f_1$



keep energy constant while scaling forces

Transparency

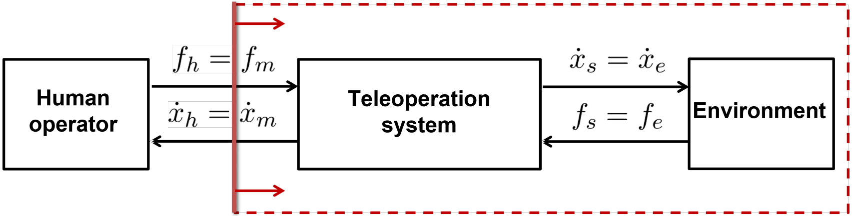
TRANSPARENCY GOAL: design local feedback loops and coordinating feedback loops at the master and slave sides to reproduce the impedance seen at the opposite end of the teleoperator

- Duplicate the effort-flow pair of the environment at the operator side and, at the same time, to reproduce the effort-flow pair of the human at the manipulator tip.
- This constrains efforts and flows to be identical,

$$\begin{aligned} \dot{x}_m &= \dot{x}_s \\ f_m &= f_s \end{aligned}$$

i.e. to have the same impedance at the (operator-master robot) and (slave robot-environment) ports

Transparency and Transmitted Impedance



$$Z_t = \frac{F_m}{\dot{X}_m} \qquad\qquad Z_e$$

Transmitted impedance: overall impedance felt by the operator (teleoperation system + environment)

The ideal conditions $\dot{x}_m = \dot{x}_s$ and $f_m = f_s$ are equivalent to require

$$Z_t = Z_e$$

Transparency is a function only of the teleoperator system, not of the task impedance nor of the hand impedance

Substituting $f_s = Z_e \dot{x}_s$ into

$$\begin{bmatrix} f_m \\ \dot{x}_m \end{bmatrix} = \begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} \begin{bmatrix} \dot{x}_s \\ -f_s \end{bmatrix}$$

we get

$$f_m = \underbrace{(H_{11} - H_{12} Z_e)(H_{21} - H_{22} Z_e)^{-1}}_{\triangleq Z_t} \dot{x}_m$$

Then the constraint $Z_t = Z_e$ implies

$$\begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} =$$

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$$\begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

With the other notation for the hybrid matrix

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we get

$$f_m = \underbrace{\bar{H}_{11} - \frac{\bar{H}_{12}\bar{H}_{21}Z_e}{1 + \bar{H}_{22}Z_e}}_{\triangleq Z_t} \dot{x}_m$$

Then the constraint $Z_t = Z_e$ implies

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$$\begin{bmatrix} \bar{H}_{11}(s) & \bar{H}_{12}(s) \\ \bar{H}_{21}(s) & \bar{H}_{22}(s) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

NB: Ze ci serve solo per derivare le "condizioni ideali" della matrice. Non serve calcolare Ze

Perfect Transparency

Remarks:

- The external forces $f_h^\star$ and $f_e^\star$ are independent of teleoperator system behavior.
- Each element of the hybrid matrix is affected by the mechanical dynamics of the master and slave robots, and by the control architecture as well.
  - Thus it is not always possible to arbitrarily select the hybrid parameters

Good Transparency instead of Perfect Transparency

Good Transparency

In general, it would be enough to obtain *good transparency at low frequencies*, so the operator can accurately determine stiffness while in contact with an environment, or determine payload inertia while in free motion.

The higher the bandwidth of the transparency, the larger the degree of telepresence.
▷ *Stability becomes a limiting factor in achievable bandwidths*

To guide the trade-off between stability and performance the designers have to answer the following questions:

1. What degree of transparency is necessary to accomplish a given set of teleoperation tasks?
2. What degree of transparency is possible to achieve?
3. What are suitable control architectures for guaranteeing the necessary transparency?

Good Transparency

To define when transparency is good, performance indices have to be defined to measure how far the system is from perfect transparency.

Examples of errors to be minimized

- position tracking

$$e_p = W_p(x_s - \kappa_p x_m)$$

- force rendering

$$e_f = W_f(f_s - \kappa_f f_m)$$

- impedance coupling

$$e_i = W_{zm}(\dot{x}_m - Z_t^{-1} f_m)$$

The *transfer functions* $W_p(s)$, $W_f(s)$, $W_z(s)$ weight more the frequency range where it is important to guarantee transparency.

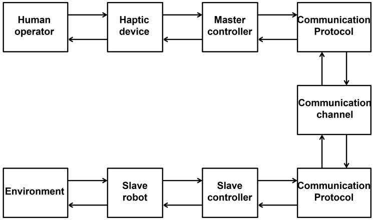
The *crossover frequency* of the weighting functions should be at least equal to the desired operation bandwidth.

Good Transparency

- For the *safety of the human operator*, the master robot must remain stable when not held by a human operator. A closed-loop position controller keeps the master robot stationary when not held by an operator.

- For the *security of the object being manipulated*, the slave robot must remain stable, if the communication between the slave and master is cut off accidentally. A closed-loop position controller on the slave robot keeps the slave robot stationary in these cases.

What about the visual feedback?



- Visual feedback does not play any role in the system stability
- Visual feedback is clearly important to make a teleoperation system usable
- Visual feedback is affected by the delay of the communication channel