PHYSICAL HUMAN-ROBOT INTERACTION

4-Channel Bilateral Teleoperation

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Outline

Problem statement

Intentional force and Visual feedback

Human and environment impedance

PROJECT

Extension of the Four-Channel teleoperation

Two-Channel teleoperation

Three-Channel teleoperation

PROJECT

Problem statement

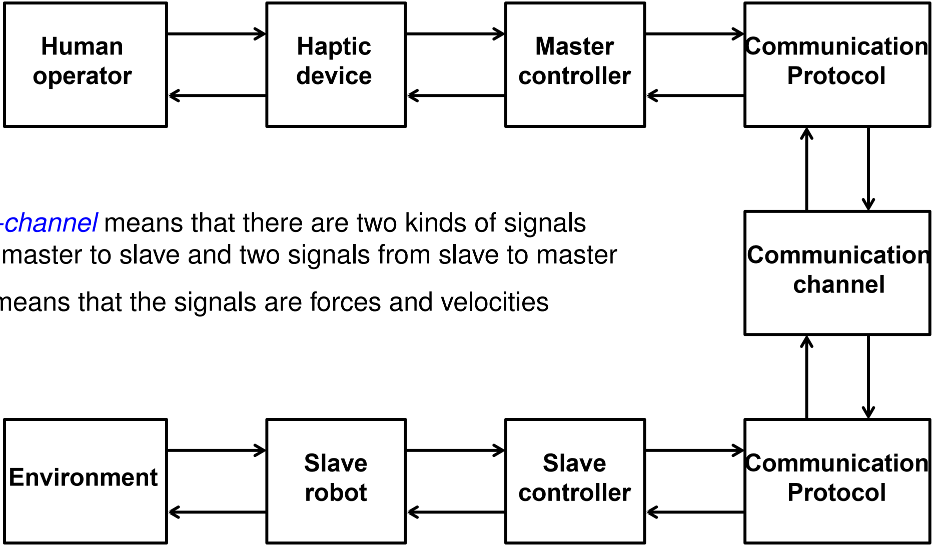
Different kinds of control architectures based on the number of virtual channels (i.e. number of signals master and slave send and receive):

- Two-channel architecture
- Three-channel architecture
- Four-channel architecture

or on the location of the controller(s)

- Centralized controller
- Decentralized controllers

have been proposed during the past 30 years



Four-channel means that there are two kinds of signals from master to slave and two signals from slave to master

F-V means that the signals are forces and velocities

Four-Channel F-V Teleoperation

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ALTAIR

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Stability and Transparency in Bilateral Teleoperation

Dale A. Lawrence

***Abstract*—Space applications of telerobots are characterized by significant communication delays between operator commands and resulting robot actions at a remote site. A high degree of telepresence is also desired to enable operators to safely conduct teleoperation tasks. This paper provides tools for quantifying teleoperation system performance and stability when communication delays are present. A general multivariable system architecture is utilized which includes all four types of data transmission between master and slave: force and velocity in both directions. It is shown that a proper use of all four channels is of critical importance in achieving high performance telepresence in the sense of accurate transmission of task impedances to the operator. It is also shown that transparency and robust stability (passivity) are conflicting design goals in teleoperation systems. The analysis is illustrated by comparing transparency and stability in two common architectures, as well as a recent "passivated" approach and a new "transparency optimized" architecture, using simplified one degree of freedom examples.**

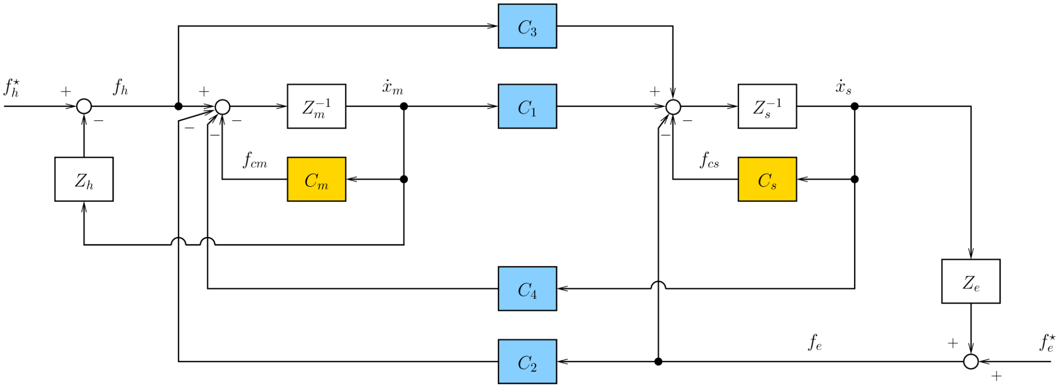
I. Introduction

TELEOPERATION has the potential to play a significant role in future space operations, such as the construction, larger delays introduced by signal relaying, multiplexing, and coding/decoding. At some large delay, direct telemanipulation becomes impossible. Thus, the desire to utilize the unparalleled manipulation capability of a human operator must be balanced against the limits of technology in providing telepresence performance. To determine the role of direct (bilateral) teleoperation in space operations, e.g., to decide at what point communication delay becomes prohibitive, the limits of performance in the presence of delay must be more fully understood. Unfortunately, existing performance evaluations (e.g., [2]) have been carried out on teleoperation systems which do not provide optimal performance, hence the resulting judgements on the effects of communication delay may be premature. This paper presents an architecture which can provide optimal telepresence performance, and investigates the effects of communication delay in that context.

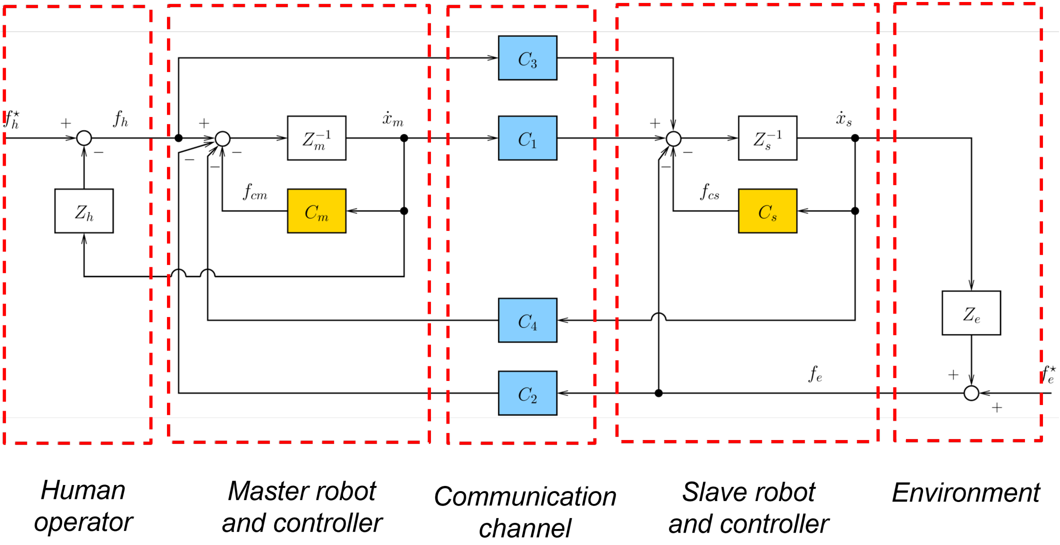
Until very recently, designs for teleoperation systems have focussed on static capabilities and kinematics, e.g., degrees of

Four-Channel F-V Teleoperation

We start with the architecture proposed by Lawrence and we show that this architecture can be specialized to obtain other teleoperation schemes according to the available sensors



Four-Channel F-V Teleoperation



Assumptions

Assumptions:

A1 No communication delays between slave side and master side

A2 Perfect knowledge of the master and slave robot dynamics

A3 Force and velocity (position) measurements at the master and slave side are available

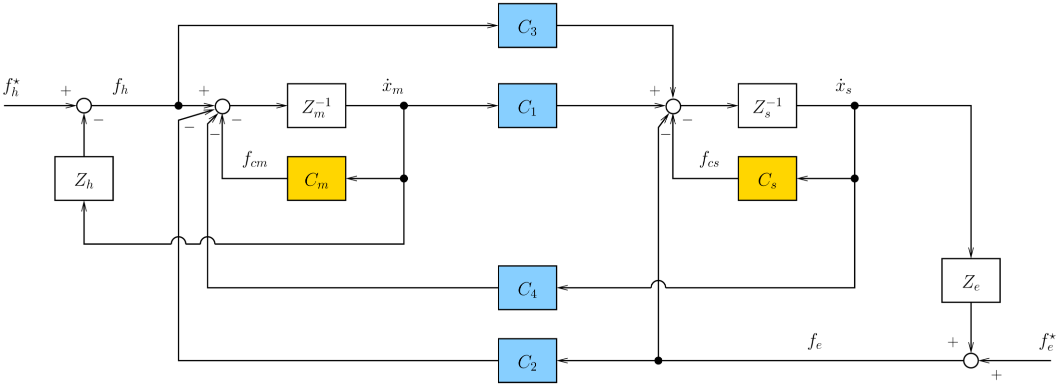
Control problem:

- Design the yellow controllers (i.e. *inner controllers*) and the blue controllers (i.e. *coordination controllers*)

Criterion:

- Perfect transparency

Meaning of the arrows



Transmitted impedance (Lawrence, ...)

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

Transmitted impedance (Hannaford, Hash-Zaad Salcudean, ...)

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

Z-width

Analysis of the transmitted impedance for the extreme cases:

- Free motion ($Z_e = 0$): the slave robot is not interacting with the environment

$$Z_t^{min} = Z_t|_{Z_e=0} = \frac{H_{11}}{H_{21}}, \qquad \left(Z_t^{min} = Z_t|_{Z_e=0} = \bar{H}_{11} \right)$$

- Hard environment ($Z_e \to \infty$): the slave robot is interacting with an undeformable environment

$$Z_t^{max} = Z_t|_{Z_e\to\infty} = \frac{H_{12}}{H_{22}}, \qquad \left(Z_t^{max} = Z_t|_{Z_e\to\infty} = \frac{\Delta \bar{H}}{\bar{H}_{22}} \right)$$

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The *Z-width* is a performance measure of the dynamic range of the achievable impedance

$$Z_t^{width} = Z_t^{max} - Z_t^{min} = \frac{H_{12}H_{21} - H_{11}H_{22}}{H_{22}H_{21}}, \qquad \left(Z_t^{width} = Z_t^{max} - Z_t^{min} = \frac{-\bar{H}_{12}\bar{H}_{21}}{\bar{H}_{22}} \right)$$

Hybrid transfer matrix

From the expression

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

it is easy to compute each elements of the hybrid matrix (Lawrence) as a function of the controllers ($C_m, C_s, C_1, \ldots, C_4$) and the master/slave robot impedance (Z_m, Z_s)

Hybrid transfer matrix

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$$\begin{aligned}
H_{11} &:= \left.\frac{f_m}{\dot{x}_s}\right|_{f_s=0} = (Z_m + C_m)D(Z_s + C_s - C_3 C_4) + C_4 \\
H_{12} &:= -\left.\frac{f_m}{f_s}\right|_{x_s=0} = -(Z_m + C_m)D(I - C_3 C_2) - C_2 \\
H_{21} &:= \left.\frac{\dot{x}_m}{\dot{x}_s}\right|_{f_s=0} = D(Z_s + C_s - C_3 C_4) \\
H_{22} &:= -\left.\frac{\dot{x}_m}{f_s}\right|_{\dot{x}_s=0} = -D(I - C_3 C_2)
\end{aligned}$$

where $D = (C_1 + C_3 Z_m + C_3 C_m)^{-1}$.

Hybrid transfer matrix: Perfect transparency

The perfect transparency

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

we need to set

$$\begin{aligned} H_{11} &= (Z_m + C_m)D(Z_s + C_s - C_3 C_4) + C_4 = 0 \\ H_{12} &= -(Z_m + C_m)D(I - C_3 C_2) - C_2 = -1 \\ H_{21} &= D(Z_s + C_s - C_3 C_4) = 1 \\ H_{22} &= -D(I - C_3 C_2) = 0 \end{aligned}$$

These conditions are satisfied when

$$\begin{aligned} C_3 C_2 &= I \\ C_4 &= -(Z_m + C_m) \\ C_1 &= Z_s + C_s \\ C_2 &= I \end{aligned}$$

Hybrid transfer matrix: Perfect transparency

Remarks:

- The same conditions hold for the hybrid matrix $\bar{H}(s)$
- In telefunctioning it could be useful to have $C_2 \neq 1$:
  - $C_2 < 1$ to reduce operator's fatigue (i.e. attenuation)
  - $C_2 > 1$ to increase operator's level of sensitivity (i.e. magnification)

Problem:
The control laws for C_1 and C_4 require acceleration measurements due to the inertial part of the robot impedance Z_m and Z_s.

Workaround:
Good low-frequency transparency can be obtained using simpler control laws which only require position and velocity measurements to implement C_1 and C_4.

Hybrid transfer matrix: Perfect transparency

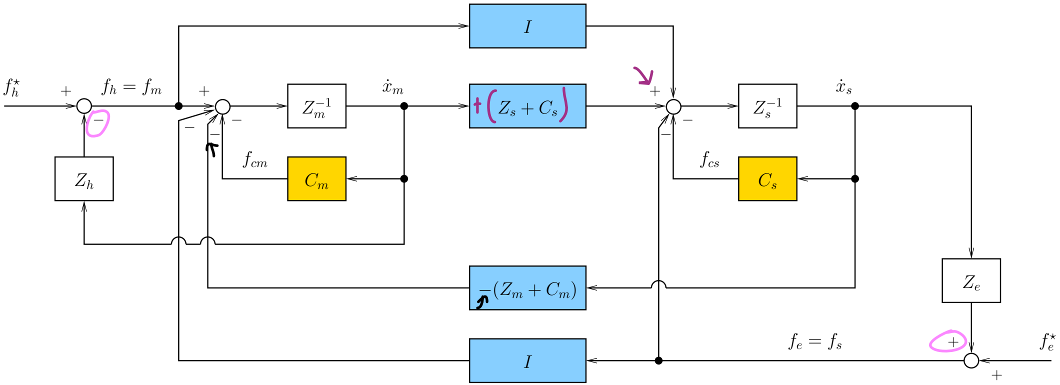
Physical interpretation of Perfect transparency

To achieve transparency, the master and slave robot dynamics have to be canceled out using inverse dynamics and the forces fed forward have to match the net forces exerted by the operator and the environment

Observation

Perfect transparency might not be desirable: the master and slave robots would drift around if neither was connected to the operator and/or the environment.

Position error dynamics



Transparent Bilateral Teleoperation under Position and Rate Control Septimiu E. Salcudean, Ming Zhu, Wen-Hong Zhu and Keyvan Hashtrudi-Zaad. The International Journal of Robotics Research 2000; 19; 1185

Position error dynamics

Using the proper expressions for C_i we have

$$\begin{aligned}
\dot{x}_s &= (Z_s + C_s)^{-1} \left[f_m - f_s + (Z_s + C_s)\dot{x}_m \right], && \text{(slave side)} \\
\dot{x}_m &= (Z_m + C_m)^{-1} \left[f_m - f_s + (Z_m + C_m)\dot{x}_s \right], && \text{(master side)}
\end{aligned}$$

and we end up with

$$\begin{aligned}
f_m - f_s &= (Z_m + C_m)(\dot{x}_m - \dot{x}_s) \\
f_m - f_s &= (Z_s + C_s)(\dot{x}_s - \dot{x}_m)
\end{aligned}$$

Taking the difference, the *position error dynamics* has to satisfy the autonomous differential equation

$$s(Z_m + C_m + Z_s + C_s)(x_m - x_s) = 0$$

so the position is defined wrt the master impedance, the slave impedance (le Z) and the inner controllers

Position error dynamics

suppose you have a position offset.
if you have a controller on the error position you can compensate on this offset
but if you have a pi controller on the error velocity an offset in position cannot be compensated, because when you take the derivative of the constant offset it is 0

With PI local controllers on velocity, ($\sim$ PD local controllers on position)

because we concentrate more on force and velocity

$$C_m = B_m + \frac{K_m}{s}, \qquad C_s = B_s + \frac{K_s}{s}$$

and simple inertia for the robot dynamics

$$Z_m^{-1} = \frac{1}{M_m s}, \qquad Z_s^{-1} = \frac{1}{M_s s},$$

these two transf functions map torque into velocity (-> output is velocity)

the teleoperation system is stable, and the slave tracks the master position asymptotically (i.e. zero steady-state error).

REMARK 1. It is interesting to note that the end point impedance of the system viewed from the slave side equals the operator impedance (*symmetry*).

REMARK 2. Perfect transparency guarantees infinite Z-width.

No acceleration measurements

When acceleration measurements are not available (as usual), we have to approximate the "ideal" controllers C_1 and C_4 by approximating the impedance of the master and slave robots

Causal functions $\hat{Z}_m(s)$ and $\hat{Z}_s(s)$ instead of $Z_m(s) = M_m s$ and $Z_s(s) = M_s s$, respectively

not causal wrt velocity

$$
\begin{aligned}
C_4 &= -(\hat{Z}_m + C_m) \\
C_1 &= \hat{Z}_s + C_s
\end{aligned}
$$

where

non è un derivatore puro, ma almeno c'è uno zero in 0

$i = 1$

$$A_0 + \frac{A_1}{s} = \frac{A_0 s + A_1}{s}$$

$$\hat{Z}_x = A_0 + \sum_{i>0} \frac{A_i}{s^i} \Longrightarrow$$

causal wrt velocity

quindi abbiamo una s al numeratore (obiettivo), ma abbiamo dovuto aggiungere un integratore

At low frequencies, the transparency is still accurate enough whereas the value of transmitted impedance Z_t becomes increasingly inaccurate as a representation of the environmental impedance Z_e.

No robot models

When the model of the master and slave robots (Z_m, Z_s) are not available or not accurate enough (e.g. time-varying), the controllers can be designed by simply ignoring such contributions

$$
\begin{aligned}
C_1 &= C_s + \cancel{Z_m} \\
C_2 &= I \\
C_3 &= I \\
C_4 &= -C_m
\end{aligned}
$$

ignore

The controller C_m and C_s are assumed known.

The relationships between $f_m - f_s$ and $\dot{x}_m - \dot{x}_s$ are now equal to

$$
\begin{aligned}
f_m - f_s &= Z_m \dot{x}_m + C_m(\dot{x}_m - \dot{x}_s) \\
f_m - f_s &= Z_s \dot{x}_s + C_s(\dot{x}_s - \dot{x}_m)
\end{aligned}
$$

If $Z_m = Z_s$ (e.g. the same kind of robot) then

$$s(Z_m + C_m + C_s)(x_m - x_s) = 0$$

final theorem of laplace transf.
per t->inf (s->0), then
(xm-xs) = 0, quindi l errore di posizione va a 0 (obiettivo raggiunto)

No robot models

Also in this case, the errors converges to zero.

However, there some differences.

Remarks:

- the operator feels the sum of the environment impedance and the master impedance

$$Z_t = Z_m + Z_e$$

in perfett transparency we had Zt = Ze
ma adesso che non conosciamo il modello del robot, non possiamo cancellare la sua impedenza, e quindi l'operatore sente anche l'impedenza del robot

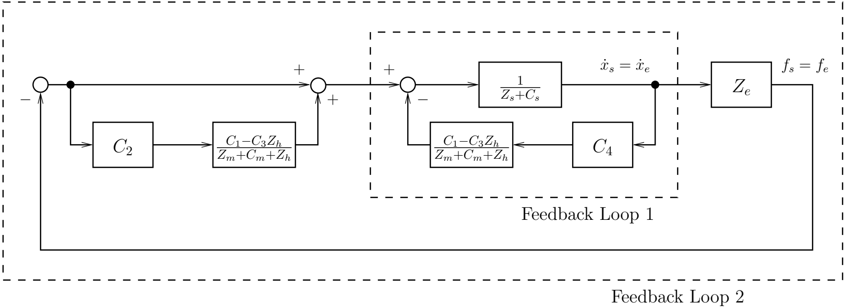
- The impedance transmitted by the slave to the environment is equal to the impedance of the human hand plus the slave impedance

$$Z_{end} = Z_m + Z_h \qquad (Z_m = Z_s)$$

same...

Stability

If *accurate models* of the operator and environment impedance are available (Z_h, Z_e), it is possible to use standard control tools to prove the stability of the closed-loop system.



Stability can be proved by applying the *Nyquist criterion* or the *Bode theorem* to the feedback loops 1 and 2, created by reorganizing the block diagram of the teleoperator system. Or, checking the poles of the closed-loop transfer functions.

Under the assumptions:

A1 $Z_m = Z_s$

A2 $\begin{cases} C_1 = C_s \\ C_2 = I \\ C_3 = I \\ C_4 = -C_m \end{cases}$

the characteristic equations of the inner and the outer loops are

$$
\begin{aligned}
FL1_{open} + 1 &= \frac{(Z_s + C_s + C_m)(Z_h + Z_m)}{(Z_m + C_m + Z_h)(Z_s + C_s)} = 0 \\
FL2_{open} + 1 &= \frac{(Z_h + Z_m + Z_e)(Z_m + C_m + C_s)}{(Z_m + Z_h)(Z_s + C_s + C_m)} = 0
\end{aligned}
$$

Stability

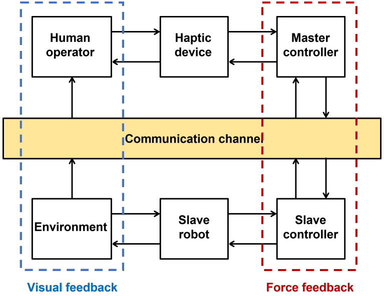
In real life:

- Z_h and Z_e are not known and may change during the teleoperation.
- The mathematical models of the master and slave robots are not linear (and Multi-Input Multi-Output) and the parameters not always known.
- Position measurements are affected by noise and so the estimation of velocities should be done with lots of care.

A different way to prove stability is needed!

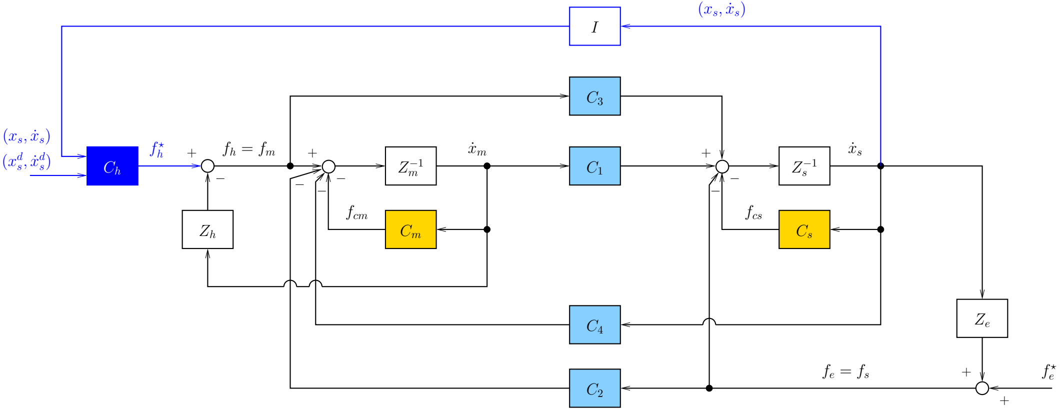
Intentional force and Visual feedback

In the present scenario, the network is modeled as a simple connection, i.e. no communication delay.



- How can we model the visual feedback in a SISO teleoperation system?
- What does the visual feedback affect?

The operator will $f_h^\star$ is modeled as the output of a controller C_h comparing the desired position/velocity for the slave $(x_s^d, \dot{x}_s^d)$ with its actual position/velocity $(x_s, \dot{x}_s)$



Intentional force and Visual feedback

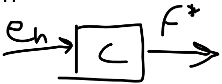
Modeling C_h as a PD controller, we have

$$f_h^\star(t) \quad = \quad P_h(x_s^d(t) - x_s(t)) + D_h(\dot{x}_s^d(t) - \dot{x}_s(t))$$

Let

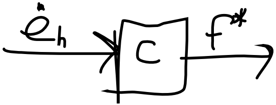
$$e_h(t) := x_s^d(t) - x_s(t), \qquad \dot{e}_h(t) := \dot{x}_s^d(t) - \dot{x}_s(t)$$

then C_h mapping $e_h(t)$ into $f_h^\star(t)$ has the following transfer function



$$C_h(s) = P_h + D_h\, s$$

whereas if C_h maps $\dot{e}_h(t)$ into $f_h^\star(t)$ we have



$$\bar{C}_h(s) = P_h \frac{1}{s} + D_h$$

Human and environment impedance

Human impedance

The impedance of the operator arm mapping velocity into force is

$$Z_h(s) = J_h s + B_h \cancel{\left(+ K_h \frac{1}{s} \right)}$$

nel caso del braccio umano non ha senso usare
la stiffness (-> molla) perchè vorrebbe dire che quando
non applica forza il braccio torna indietro
come la molla che torna indietro da sola

i.e.

$$f_h^*(t) - f_h(t) = J_h \ddot{x}_h(t) + B_h \dot{x}_h(t) \cancel{\left(+ K_h x_h(t) \right)}$$

with, e.g., $J_h = 0.5$, $B_h = 0.5$.

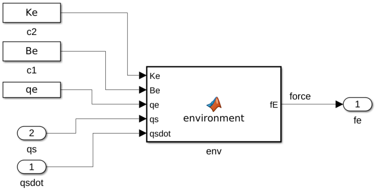
Environment impedance (contact scenario)

The environment impedance mapping velocity into force is

$$Z_e(s) = J_e s + B_e + K_e \frac{1}{s}$$

i.e. $f_e(t) = J_e \ddot{x}_s(t) + B_e \dot{x}_s(t) + K_e(x_s(t) - x_e)$

```
function fE  = environment(Ke, Be, qe, qs, qsdot)
if qs > qe
    fE = Ke * (qs - qe) + Be * qsdot;
else
    fE = 0;
end
```



The SISO environment is modeled as a *damper* $B_e \in \mathbb{R}_+$ and a *spring* $K_e \in \mathbb{R}_+$.

$$B_e = 100, K_e = 200$$

The environment is locate at $x_e = 0.4$

It is also possible to take into account the *mass* J_e if we assume to move an object and not only interacting with a static deformable environment.
In that case also the acceleration $\ddot{x}_s$ is needed.

For the moment we assume

$$f_e^\star = 0.$$

This means that the environment does not inject energy into the system.

Assumptions so far:

- The whole system is continuous-time
- No uncertainty are taken into account
- No signals are affected by noise

In the future

- we assume that only positions and forces can be measured
- all the measurements are affected by noise
- velocities should be estimated from position measurements
- the controllers are digital systems
- the communication channel is modeled as a delay


Project

To do

- Implement the Single-Input Single-Output Four-channel bilateral teleoperation architecture with

$$C_m = B_m + \frac{K_m}{s}, \qquad C_s = B_s + \frac{K_s}{s}$$

$$Z_m^{-1} = \frac{1}{M_m s}, \qquad Z_s^{-1} = \frac{1}{M_s s},$$

  where $M_m = 0.5$, $M_s = 2$. Choose properly the controllers' parameters.

- What happens if

$$Z_m^{-1} = \frac{1}{M_m s + D_m}, \qquad Z_s^{-1} = \frac{1}{M_s s + D_s},$$

  with $D_m = 5$ and $D_s = 10$?

PROJECT – Assignment # 1

For the reference signal $x^d(t)$ in SISO system, it is possibile to use

- a sinusoidal signal to test the dynamic response in free motion for different frequenc~~y~~ies F_c

$$x^d(t) = A\sin(2\pi F_c t)$$

- a step response of a first-order low-pass filter with target value higher than the position of the environment x_e to test the interaction response

$$x^d(t) = \frac{2\pi F_{lp}}{s + 2\pi F_{lp}} A\delta_{-1}(t)$$

[*informal mixed notation*]

PROJECT – Assignment # 1

Plots of positions (x_m, x_s), velocities ($\dot{x}_m(t)$, $\dot{x}_s(t)$), command forces (f_{mc}, f_{sc}), interaction forces ($f_m = f_h$, $f_s = f_e$) and intentional force (f_h^*) should be provided in different scenarios

Extension of the Four-Channel teleoperation

bla bla bla

Four-Channel with a transfer function $G(s)$

If the application under study requires that master and slave velocities are related by a transfer function $G(s)$ (in case $G(s)$ is just a constant $G(s) = \kappa \gtrless 1$ with talk about amplification/attenuation)

$$\frac{\dot{x}_s}{\dot{x}_m} = \frac{1}{G}$$

it is necessary to define the controllers as follows

$$\begin{aligned} C_1 &= C_s/G \\ C_2 &= G \\ C_3 &= G \\ C_4 &= -C_m/G \end{aligned}$$

The *transmitted impedance* is again

$$Z_t = Z_m + Z_e$$

The *hybrid matrix* becomes

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

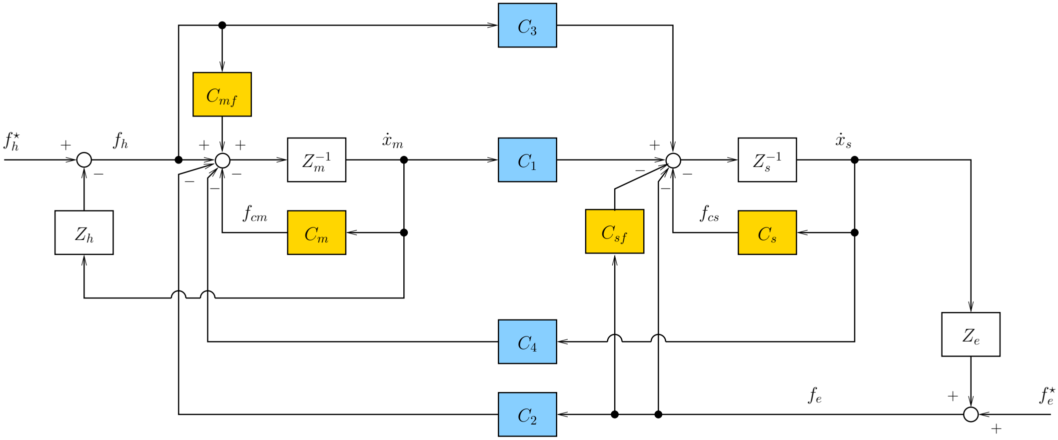
which can be re-written as

$$\begin{bmatrix} f_m \\ -G\dot{x}_s \end{bmatrix} = \begin{bmatrix} Z_m & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{x}_m \\ Gf_s \end{bmatrix}$$

Example. To have a rate-controlled system, we can set

$$G(s) = \frac{K_v s}{\tau s + 1}.$$

Four-Channel with local force loops



Hashtrudi-Zaad, Salcudean 2001

Four-Channel with local force loops

C_{mf}: master force controller
C_{sf}: slave force controller

The *hybrid transfer function* will take the form

$$
\begin{aligned}
\bar{H}_{11} &= \frac{Z_{cm}Z_{cs} + C_1 C_4}{(1+C_{mf})Z_{cs} - C_3 C_4} \\
\bar{H}_{12} &= \frac{C_2 Z_{cs} - C_4(1+C_{sf})}{(1+C_{mf})Z_{cs} - C_3 C_4} \\
\bar{H}_{21} &= -\frac{C_3 Z_{cm} + C_1(1+C_{mf})}{(1+C_{mf})Z_{cs} - C_3 C_4} \\
\bar{H}_{22} &= \frac{(1+C_{sf})(1+C_{mf}) - C_2 C_3}{(1+C_{mf})Z_{cs} - C_3 C_4}
\end{aligned}
$$

where

$$Z_{cm} = Z_m + C_m, \qquad Z_{cs} = Z_s + C_s$$

Four-Channel with local force loops

The *transmitted impedance* is equal to

$$Z_t = \frac{(Z_{cm}Z_{cs} + C_1 C_4) + [(1 + C_{sf})Z_{cm} + C_1 C_2]Z_e}{[(1 + C_{mf})Z_{cs} - C_3 C_4] + [(1 + C_{sf})(1 + C_{mf}) - C_2 C_3]Z_e}$$

The *perfect transparency* requires

$$\begin{aligned} C_1 &= Z_s + C_s = Z_{cs} \\ C_2 &= 1 + C_{mf} (\neq 0) \\ C_3 &= 1 + C_{sf} (\neq 0) \\ C_4 &= -(Z_m + C_m) = -Z_{cm} \end{aligned}$$

The *position error dynamics* is

$$\Delta_0 = (C_2 Z_{cs} + C_3 Z_{cm})(Z_h + Z_e) = 0$$

Four-Channel with local force loops

Remarks:

- if C_2 and C_3 are simple gains and the operator and environment are passive, the system remains stable if

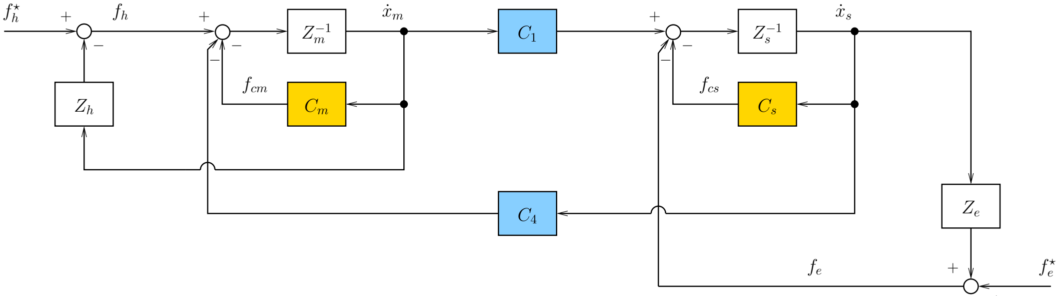
$$C_2 > -\min\left\{\frac{M_m}{M_s}, \frac{B_m}{B_s}, \frac{K_m}{K_s}\right\} C_3$$

- Force and position feedback act in opposite ways, in the sense that one softens and the other stiffens the sender device
- When the slave is in contact with a **hard environment**, contact force is the dominant signal for transmission and local force/position control has to be amplified/attenuated
- When the slave is in **free motion or in contact with a soft environment**, position or velocity is the dominant signal for transmission and local position/force control has to be amplified/attenuated
- An adaptive mechanism that automatically detects the contact type and tunes the local feedback parameters accordingly is needed

Two-Channel teleoperation

Two-Channel: Position-Position (P–P)

By setting $C_2 = C_3 = 0$, we get the *Two-Channel Position-Position (P–P) teleoperation architecture*



even if fe=0 (slave robot in free motion), the operator feels a force contribution through C4 due to the velocity of the slave (x dot s)

The only sensors are the encoders to measure the robots' position.

I cannot measure the force fh and fe (però sono ancora li perchè sono segnali fisici) --> non posso usarli in un controllore

Two-Channel: Position-Position (P–P)

Hybrid matrix

$$
\begin{aligned}
\bar{H}_{11} &= \frac{Z_{cm} Z_{cs} + C_1 C_4}{(1 + C_{mf}) Z_{cs}} \\
\bar{H}_{12} &= \frac{-C_4 (1 + C_{sf})}{(1 + C_{mf}) Z_{cs}} \\
\bar{H}_{21} &= -\frac{-C_1}{Z_{cs}} \\
\bar{H}_{22} &= \frac{(1 + C_{sf})}{Z_{cs}}
\end{aligned}
$$

Z-width

$$
Z_t^{width} = \frac{-C_1 C_4}{(1 + C_{mf}) Z_{cs}} \longrightarrow
$$

non posso avere una Z width infinita!

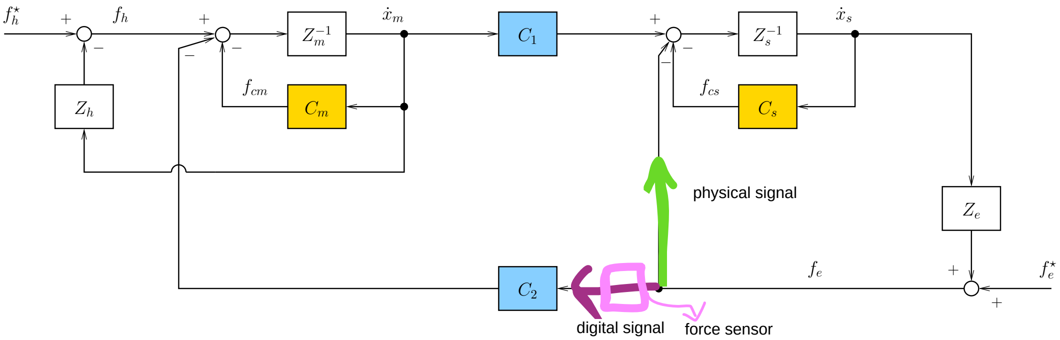
Exercise. Compute the H hybrid matrix

Two-Channel: Position-Position (P–P)

Remark:

- due to C_4, the operator perceive a force feedback even though the slave robot is not interacting with the environment.

By setting $C_3 = C_4 = 0$, we get the *Two-Channel Force-Position (F–P) teleoperation architecture*



We need the encoders to measure the robots' position and a force sensor at the slave side.

quando lo slave p in free motion fe=0 -> output di C2 è 0, quindi l'operatore sente 0 feedback (corretto!)

Two-Channel: Force-Position (F–P)

Hybrid matrix

$$
\begin{aligned}
\bar{H}_{11} &= \frac{Z_{cm}}{1 + C_{mf}} \\
\bar{H}_{12} &= \frac{C_2}{1 + C_{mf}} \\
\bar{H}_{21} &= -\frac{C_1}{Z_{cs}} \\
\bar{H}_{22} &= \frac{1 + C_{sf}}{Z_{cs}}
\end{aligned}
$$

Z-width

$$
Z_t^{width} = \frac{C_1 C_2}{(1 + C_{sf})(1 + C_{mf})}
$$

no inifnite

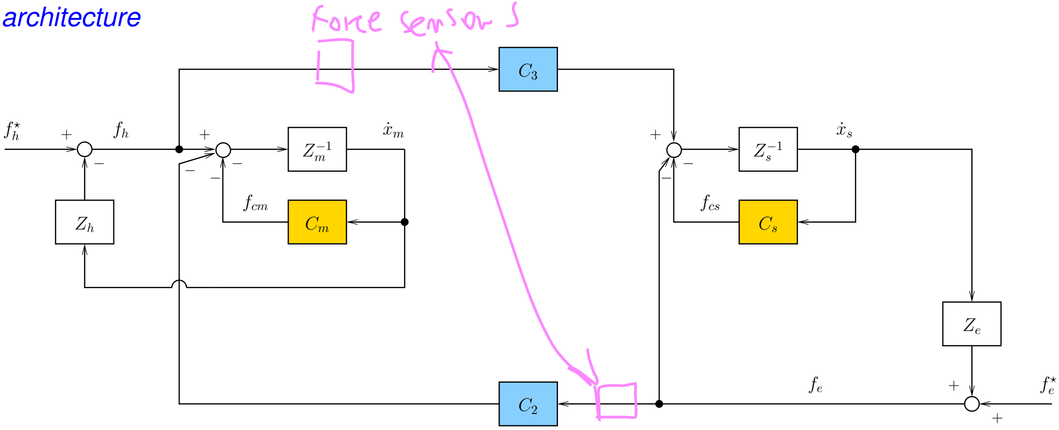
Exercise. Compute the H hybrid matrix

Two-Channel: Force-Position (F–P)

Remarks:

- to increase stability robustness, master damping and slave local force feedback should be amplified, whereas force feedforward should be attenuated
- to guarantee absolute stability for a broad range of frequencies, the feedforward control parameter C_2 has to be a low-pass filter instead of a constant
- When the slave robot does not interact with the environment, the operator perceive zero force feedback (as it should be.)

By setting $C_1 = C_4 = 0$, we get the *Two-Channel Force-Force (F–F) teleoperation architecture*



The sensors needed are the same for the Four-Channel architecture: encoders to measure the robots' position and force sensors for measuring the interaction force with the operator and with the environment.

Admittance matrix

$$
\begin{aligned}
Y_{11} &= \frac{1}{\bar{H}_{11}} &= \frac{1 + C_{mf}}{Z_{cm}} \\
Y_{12} &= \frac{\bar{H}_{12}}{\bar{H}_{11}} &= -\frac{C_2}{Z_{cm}} \\
Y_{21} &= \frac{-\bar{H}_{12}}{\bar{H}_{11}} &= -\frac{C_3}{Z_{cs}} \\
Y_{22} &= \frac{\Delta \bar{H}}{\bar{H}_{11}} &= \frac{1 + C_{sf}}{Z_{cs}}
\end{aligned}
$$

Z-width

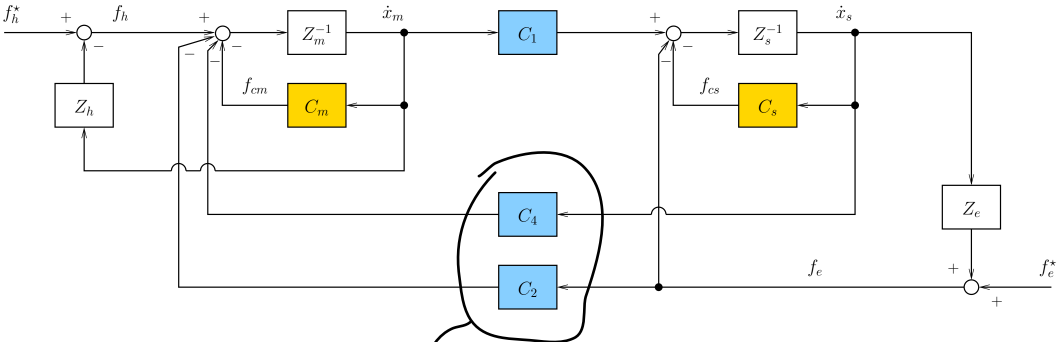
$$
Z_t^{width} := \frac{C_2 C_3 Z_{cm}}{(1 + C_{sm})((1 + C_{sf})(1 + C_{sm}) - C_2 C_3))} \rightarrow \infty
$$

Exercise. Compute the H and $\bar{H}$ hybrid matrices

Three-Channel teleoperation

cut 1 channel

By setting $C_3 = 0$, we get the *Three-Channel Position&Force-Position (PF–P) teleoperation architecture*



We need the encoders to measure the robots' position and a force sensor at the slave side.

this is the command that we send to the motor of the haptic device to provide the corresponding force feedback to the operator. nota bene che arrivano entrambi alla sommatoria, quindi è come avere C2+C4 come feedback totale quindi per l operatore è impossibile distinguere il contributo di C2 (force of interction slave-env) da quello di C4 (speed of slave)

Three-Channel: Position&Force-Position (PF–P)

Exercises.

- Compute the H hybrid matrix
- Compute the $\bar{H}$ hybrid matrix
- Compute the Z_t^{width}


Project

PROJECT – Assignment # 2

To do

- Implement the three Two-Channel bilateral teleoperation architectures and the Three-Channel bilateral teleoperation architecture

  Same parameters as in HW #1.
- What happens if transportation delays (see Simulink) are added in series at the controllers C_i (light blue blocks) in the different architectures?

just to clarify assumptions:
- so far we have assumed no communication delay

about transparency: perfect transp. can only be achieved with the 4 channel architecture (se taglio uno dei 4 segnali non posso piu avere trasparenza perfetta)