PHYSICAL HUMAN-ROBOT INTERACTION

Bilateral teleoperation: basic blocks

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Outline

Problem statement

Elementary blocks

Problem statement

Teleoperation

Idea: allow to interact with a remote (maybe dangerous) environment by using a joystick.

Key subsystems: a joystick (or haptic device), a slave robot (the device that really interact with the remote environment) and a communication channel

Role of the control: guarantee and/or enhance the coupling characteristics between the user at the master side and the environment at the slave side

Bilateral telemanipulation: the user manipulates the environment and perceives the reaction force through the haptic device (force feedback)

Interfaces

- Human-robot interface: the operator applies force and torque to the joystick
- Robot-environment interface: the end-effector of the slave robot applies force to the remote environment

Teleoperation

A crucial part: the *communication channel*.

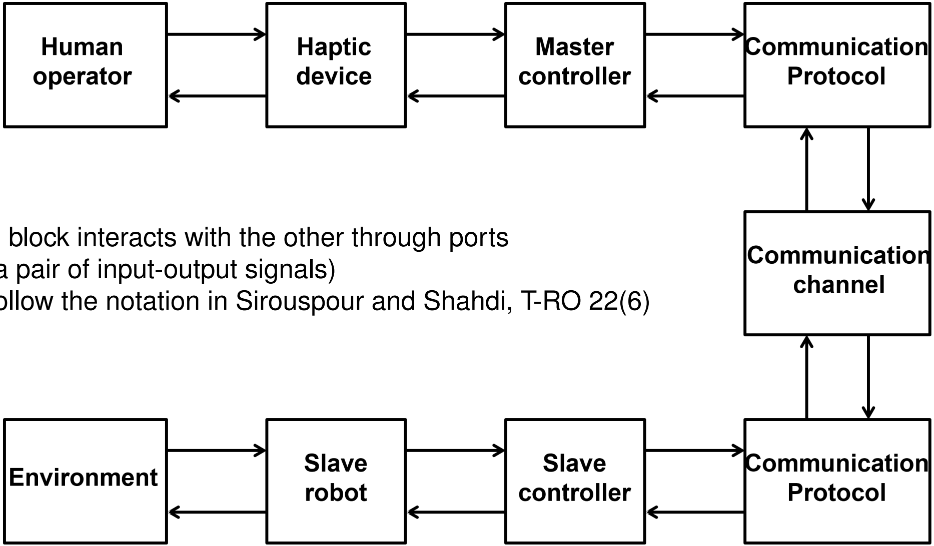
Commands or set-points from the master to the slave side and force feedback signals from the slave to the master side travel through a packet-based network

A packet-based network allows teleoperation at long distance but introduces destabilizing side-effects

Problems: delays (constant or time-varying) and packet dropouts

Elementary blocks

Block diagram



Each block interacts with the other through ports
(i.e. a pair of input-output signals)
We follow the notation in Sirouspour and Shahdi, T-RO 22(6)

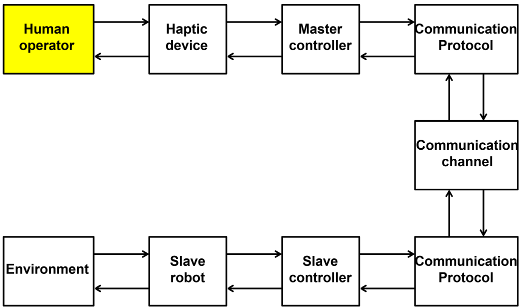
Human arm

The human intention, the psychophysical characteristic and the "mechanical behavior" of the human arm are very difficult to model. We simplify their dynamical model with second order (i.e. mass-spring-damper) differential equations.

▷ Linear and decoupled single-axis approximation

$$m_h \ddot{x}_h + b_h \dot{x}_h + k_h x_h = f_h^\star - f_h$$

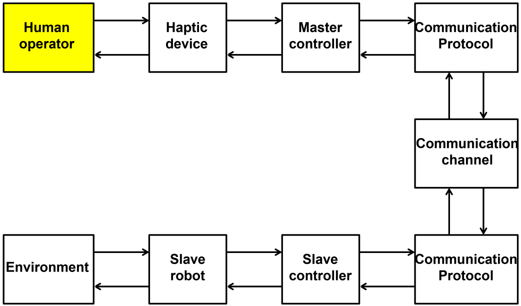
x_h: operator's position
$f_h^\star$: human intentional force
f_h: human/haptic device interaction force
m_h, b_h, k_h: mass, damping, stiffness



Intentional action

$$m_f \ddot{f}_h^\star + b_f \dot{f}_h^\star + k_f f_h^\star = n_f$$

$f_h^\star$: operator's intetional force
n_f: white Gaussian noise
f_h: human/haptic device interaction force
m_h, b_h, k_h: "equivalent" mass, damping, stiffness



Human

The human arm's dynamics can be rewritten as

$$f_h = f_h^\star - Z_h \dot{x}_h$$

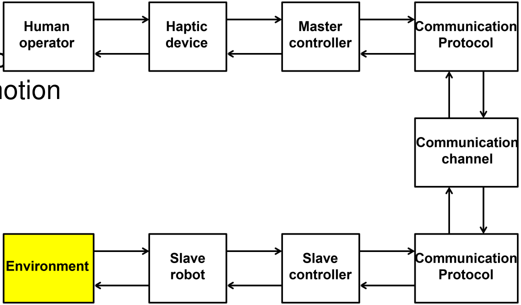
where

- $f_h^\star$ is that part of the contact force that is imposed by the muscles (ACTIVE EXOGENOUS COMPONENT), as commanded by the central nervous system,
- Z_h is the human arm impedance (or sensitivity function) and maps the master robot position ($x_h = x_m$) into the contact force (PASSIVE FEEDBACK COMPONENT). It is determined primarily by the physical and neural properties of the human arm.

  Z_h plays an important role in the stability and performance of a bilateral teleoperation system

Environment

$$f_e = \begin{cases} m_e\ddot{x}_e + b_e\dot{x}_e + k_e(x_e - \bar{x}_e) + f_e^\star, & \text{contac} \\ 0, & \text{free motion} \end{cases}$$



f_e: environment reaction force
x_e: position of the environment (= end effector)
m_e, b_e, k_e: mass, damping, stiffness (compliant environment)
$f_e^\star$: exogenous force (usually equal to zero)

Environment

Dynamic behavior of the environment

$$f_e = Z_e \dot{x}_e + f_e^\star$$

where

- $f_e^\star$ is the ACTIVE EXOGENOUS COMPONENT at the environment side (e.g. beating heart)
- Z_e is the environment impedance (or sensitivity function) and maps the slave robot position ($x_e = x_s$) into the contact force (PASSIVE FEEDBACK COMPONENT)

  Z_e plays an important role in the stability and performance of a bilateral teleoperation system

Environment

With respect to the interaction of the slave robot with the environment, the bilateral teleoperation system can be model as a *hybrid system* with three locations:

- *Free motion*: the slave robot does not interact with the environment
- *Soft contact*: the slave interacts with a soft environment than can be modeled as a mass-spring-damper system
- *Hard contact*: the slave interacts with a rigid environment, i.e.

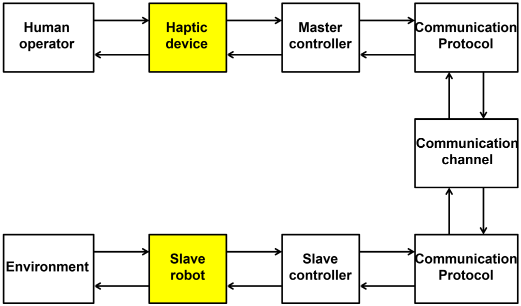
$$x_s = const, \qquad \dot{x}_s = 0$$
$$f_s \neq 0$$

The location can be determined by analyzing the relationship between the velocity and the contact force.

MIMO nonlinear model of a Robot

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + F(q,\dot{q}) + G(q) = u$$

u: command torque vector,
q: generalized coordinates
M: symmetric non singular moment of inertia matrix
C is the Coriolis and centrifugal force matrix
F frictional torques,
G gravity



Dynamic model of a robot in contact

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + F(q,\dot{q}) + G(q) = u + J^T(q)f$$

where

- f is generalized Cartesian force (forces+torques)
- $J(q)$ is the geometric Jacobian

When the master robot and the slave robot have different kinematics it is not possible to send and receive joint variables, but it is necessary to map master (slave) Cartesian pose (position+orientation) into slave (master) Cartesian pose

Dynamic model in Cartesian coordinates (or Operational space)

$$\Lambda(x)\ddot{x} + \Xi(x,\dot{x})\dot{x} + \Phi(x,\dot{x}) + \gamma(x) = J_a^{-T}(q)u + f_a$$

where x is the pose and the other matrices are obtained using the analytical Jacobian $J_a(q)$

$$f_a = T_a^{-1}(\phi)f, \quad J_a(q) = T_a(\phi)J(q)$$

Dynamic model of a robot in contact

Often, we assume that nonlinear stabilizing controllers (INNER OR PRIMARY CONTROLLERS) have been designed to yield nearly *linear and decoupled* closed-loop position systems for the master and slave robot.

Step 1. feedback linearization in Cartesian space

$$u = J_a^T(q)[\Lambda(x)v + \Xi(x,\dot{x})\dot{x} + \Phi(x,\dot{x}) + \gamma(x)]$$
$$\ddot{x} = v + f_{ext}$$

Step 2. set a dynamic impedance model

$$v = f_c - M^{-1}(B\dot{x} + Kx)$$
$$M\ddot{x} + B\dot{x} + Kx = f_c$$

This lets us assume that the robots' closed loop dynamics can be approximated by *transfer function matrices* (or linear state-space model representations) .

Observations:

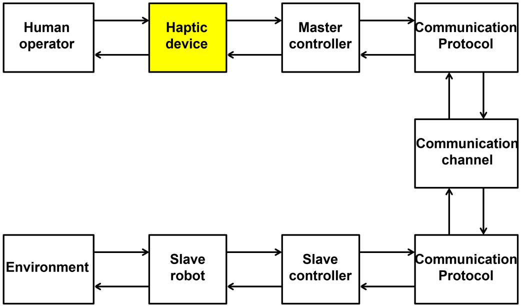
- The closed-loop position controller also eliminates the effects of friction forces in their joints and transmission mechanism.
- The design of the primary stabilizing compensator allows to focus on the robustness of the master robot and the slave robot local control loops without getting involved in the dynamics of the human arm (master side), the dynamics of the environment (slave side), and the communication delay
- Issue 1: robustness of the model-based nonlinear feedback linearization
- Issue 2: it is needed a further layer for checking the singularity points

Robot at the operator side

Master robot linear single-axis approximation

$$m_m\ddot{x}_m + b_m\dot{x}_m + k_m x_m = f_{mc} + f_h$$

where x_m: master robot position
f_{mc}: control force due to the master controller
f_h: human/haptic device interaction force
m_m, b_m, k_m: mass, damping, stiffness

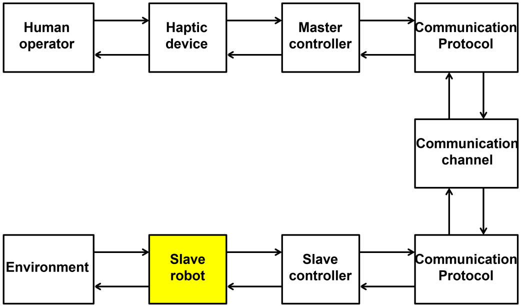


Robot at the remote side

Slave robot linear single-axis approximation

$$m_s \ddot{x}_s + b_s \dot{x}_s + k_s x_s = f_{sc} - f_e$$

where x_s: slave robot position
f_{sc}: control force due to the slave controller
f_e: environment reaction force
m_s, b_s, k_s: mass, damping, stiffness



Master and slave robot

$$
\begin{aligned}
m_m\ddot{x}_m + b_m\dot{x}_m + k_m x_m &= f_{mc} + f_h \\
m_s\ddot{x}_s + b_s\dot{x}_s + k_s x_s &= f_{sc} - f_e
\end{aligned}
$$

Human operator and Environment

$$m_h\ddot{x}_h + b_h\dot{x}_h + c_h x_h = f_h^{\star} - f_h$$

$$x_h = x_m \quad \text{during contact}$$

$$m_e\ddot{x}_e + b_e\dot{x}_e + c_e x_e = f_e$$

$$x_e = x_s \quad \text{during contact}$$

IMPEDANCE: ratio between effort (i.e. force) and flow (i.e. velocity)

ADMITTANCE: ratio between flow (i.e. velocity) and effort (i.e. force)

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

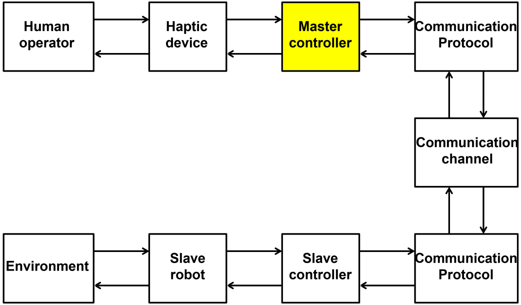
Master robot
$$Z_m^{-1}(s) = \frac{sX_m(s)}{F_{mc}(s) + F_h(s)} = \frac{s}{m_m s^2 + b_m s + k_m}$$

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

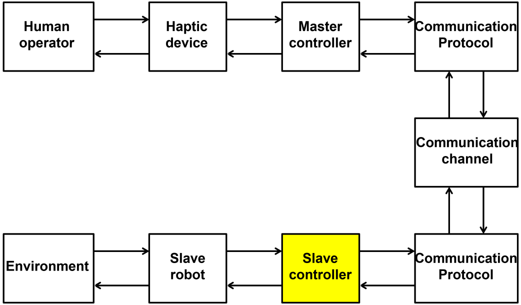
Master controller

$$
\begin{aligned}
f_{mc} &= \begin{bmatrix} K_{mpm} + K_{mvm}\frac{d}{dt} + K_{mam}\frac{d^2}{dt^2} & K_{mfm} \end{bmatrix} \begin{bmatrix} x_m \\ f_m \end{bmatrix} - \\
&\quad - \begin{bmatrix} K_{mps} + K_{mvs}\frac{d}{dt} + K_{mas}\frac{d^2}{dt^2} & K_{mfs} \end{bmatrix} \begin{bmatrix} x_s \\ f_s \end{bmatrix} \\
&= \begin{bmatrix} P_m(s) & Q_m(s) \end{bmatrix} \begin{bmatrix} \dot{x}_m \\ f_m \end{bmatrix} - \\
&\quad - \begin{bmatrix} R_m(s) & S_m(s) \end{bmatrix} \begin{bmatrix} \dot{x}_s \\ f_s \end{bmatrix}
\end{aligned}
$$



Slave controller

$$
\begin{aligned}
f_{sc} &= \begin{bmatrix} K_{sps} + K_{svs}\frac{d}{dt} + K_{sas}\frac{d^2}{dt^2} & K_{sfs} \end{bmatrix} \begin{bmatrix} x_s \\ f_s \end{bmatrix} - \\
&\quad - \begin{bmatrix} K_{spm} + K_{svm}\frac{d}{dt} + K_{mas}\frac{d^2}{dt^2} & K_{sfm} \end{bmatrix} \begin{bmatrix} x_m \\ f_m \end{bmatrix} \\
&= \begin{bmatrix} P_s(s) & Q_s(s) \end{bmatrix} \begin{bmatrix} \dot{x}_s \\ f_s \end{bmatrix} - \\
&\quad - \begin{bmatrix} R_s(s) & S_s(s) \end{bmatrix} \begin{bmatrix} \dot{x}_m \\ f_m \end{bmatrix}
\end{aligned}
$$



Slave controller

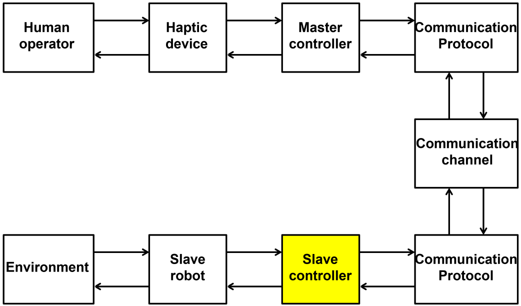
Slave D controller

$$f_{cs} = k_{D,cs}(\dot{x}_m - \dot{x}_s)$$

Slave PD controller

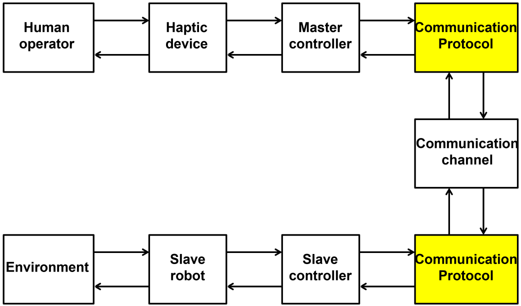
$$f_{cs} = k_{D,cs}(\dot{x}_m - \dot{x}_s) + k_{P,cs}(x_m - x_s)$$

or (e.g.) impedance controller, force controller, model predictive controller, . . .



Communication Protocols

crypting / decrypting the data travelling on the communication channel (safety, security, privacy, ...)



Communication Channel

$$u_{rcv}(t) = \nu_n(t) u_{sent}(t - T_n(t))$$

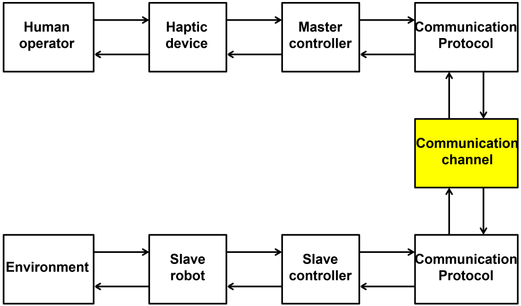
where

u_{rcv} received signal

u_{sent} sent signal

$T_n(t)$ transmission delay at time t

$\nu_n(t) \in \{0, 1\}$ binary variable related to the packet loss rate at time t



Key specifications

Key concepts:

- *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