PHYSICAL HUMAN-ROBOT INTERACTION

Stable Adaptive Teleoperation
by G Niemeyer and JJ Slotine

Riccardo Muradore

UNIVERSITÀ di VERONA
Dipartimento di INFORMATICA

Paper

Stable Adaptive Teleoperation

Günter Niemeyer and Jean-Jacques E. Slotine, *Member, IEEE*

(*Invited Paper*)

Abstract—Telerobotics, the body of science and technology which bridges human control and purely autonomous machines, is expected to be a merging point of modern developments in robotics, control theory, cognitive science, machine design, and computer science. Besides traditional applications in space, subsea, and handling of hazardous material, many new potential uses of advanced telerobotic systems have recently been suggested or explored, such as safety applications or microsurgery.

This paper studies how the existence of transmission time-delays affects the application of advanced robot control schemes to effective force-reflecting telerobotic systems, which would best exploit the presence of the human operator while making full use of available robot control technology and computing power. A physically motivated, passivity-based formalism is used to provide energy conservation and stability guarantees in the presence of transmission delays. The notion of wave variable is utilized to characterize time-delay systems and leads to a new configuration for force-reflecting teleoperation. The effectiveness of the approach is demonstrated experimentally. Within the same framework, an adaptive tracking controller is incorporated for the control of the remote robotic system and can be used to simplify, transform, or enhance the remote dynamics perceived by the operator.

I. Introduction

TELEROBOTICS (under various names) has a long and rich history (see, e.g., [11, and references therein]). It is likely to provide a common field of research and applications to many

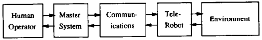
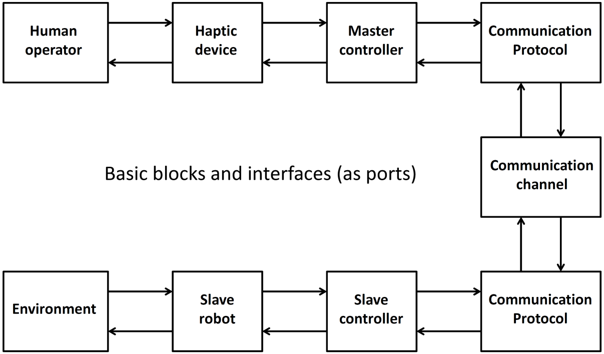


Fig. 1. Structure of the teleoperation system.

Many reasons can also be cited for using advanced control techniques to simplify the perceived remote dynamics. The operator of a complex teleoperation system should not be expected to deal with the inherent robotic or control issues—he or she has real work to do. For instance, a marine biologist remotely studying or sampling some unknown organisms in a cluttered underwater environment should not be expected to fight rapid variations in currents or drag, or to deal with the nonlinear dynamic couplings in some sophisticated underwater manipulator arm. For him or her, the remote robot should act and feel like a video game. In addition, the transmission time delays typical in many telerobotic applications make it all the more important to provide consistently high performance locally at the remote manipulator, limiting the need for corrective actions by the operator. The remote dynamics may also be transformed or enhanced so as to provide the operator with clearer cues or help in decision-making; e.g., through proper frequency shaping of the sensed signals.

Motivation

- force feedback improves operator's ability to perform complex tasks
- transmission time-delays affects stability of force-reflecting telerobotics systems
- passivity-based formalism provides energy conservation (i.e. stability)
  - delays
  - interaction with an unknown environment
- notion of wave variables and wave transmission



Basic blocks and interfaces (as ports)

Separated multiple ports allow to concentrate on the critical aspects (in the present case the communication channel)

Energy and Power

A system is passive if the power P is either stored or dissipated, i.e.

$$P = u^T y = \frac{dE}{dt} + P_{diss}$$

where u is the input vector, y the output vector, and P_{diss} is a non-negative power dissipation function.

This means that the total energy E supplied up to time t is limited to the initial stored energy (i.e. lower bounded by the negative initial energy)

$$\int_0^t P ds = \int_0^t u(s)^T y(s) ds = E(t) - E(0) + \int_0^t P_{diss}(s) ds \geq -E(0)$$

A system is lossless if $P_{diss}(t) = 0, \forall t$

passivity => simple stability (not asympt. stab)

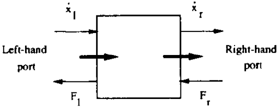
Stability and Passivity

Strong relationship between passivity and stability via Lyapunov method: stored energy as Lyapunov function.

Niemeyer-Slotine

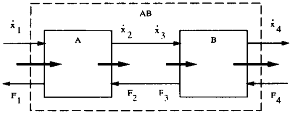
2-Port Elements

Power is **positive** if it enters the system and increases the stored energy



$$P = \dot{x}_l^T F_l - \dot{x}_r^T F_r$$

This sign definition is useful for deriving the passivity property of cascading 2-port elements:



$\dot{x}_2 = \dot{x}_3$

$F_2 = F_3$

$$\begin{aligned} P &= \dot{x}_1^T F_1 - \dot{x}_4^T F_4 \\ &= \underbrace{\boxed{\dot{x}_1^T F_1 - x_2^T F_2}}_{A} + \underbrace{\boxed{x_3^T F_3 - \dot{x}_4^T F_4}}_{B} \\ &= \frac{dE^A}{dt} + P^A_{diss} + \frac{dE^B}{dt} + P^B_{diss} = \frac{dE^{AB}}{dt} + P^{AB}_{diss} \end{aligned}$$

$E^{AB} := E^A + E^B$ lower-bounded energy storage function

$P^{AB}_{diss} := P^A_{diss} + P^B_{diss}$ non-negative power dissipation function

Wave scattering separates the total power flow into the power input ($\rightarrow$ input wave) and the power output ($\rightarrow$ output wave)

$$P = \dot{x}_l^T F_l - \dot{x}_r^T F_r = \underbrace{\frac{1}{2} u_l^T u_l - \frac{1}{2} v_l^T v_l}_{} + \underbrace{\frac{1}{2} u_r^T u_r - \frac{1}{2} v_r^T v_r}_{}$$

where u_l, u_r are input waves (they increase the power flow) and v_l, v_r are output waves (they decrease the power flow).

the relationship between the power variables (velocity and force) and wave variables (u, v) are purely algebraic and always invertible, i.e. you can always go from power to wave and go back

$$\dot{x}_l, F_l \longleftrightarrow u_l, v_l$$

$$\dot{x}_r, F_r \longleftrightarrow u_r, v_r$$

$$\dot{x}^T F = \frac{1}{2} \overbrace{u^T u}^{\text{input wave variables}} - \frac{1}{2} \overbrace{v^T v}^{\text{output wave variables}} = \frac{1}{2}\left(\|u\|^2 - \|v\|^2\right) \gtrless 0$$

Wave scattering separates the total power flow into the power input ($\rightarrow$ input wave) and the power output ($\rightarrow$ output wave)

$$P = \dot{x}_l^T F_l - \dot{x}_r^T F_r = \underbrace{\frac{1}{2}u_l^T u_l - \frac{1}{2}v_l^T v_l}_{} + \underbrace{\frac{1}{2}u_r^T u_r - \frac{1}{2}v_r^T v_r}_{}$$

where u_l, u_r are input waves (they increase the power flow) and v_l, v_r are output waves (they decrease the power flow).

Relating wave scattering to passivity, a system is passive if the energy provided by the output waves is limited to the energy received via the input waves:

$$\int_0^t \frac{1}{2}v^T(\tau)v(\tau)d\tau \leq \int_0^t \frac{1}{2}u^T(\tau)u(\tau)d\tau, \qquad u := \begin{bmatrix} u_l \\ u_r \end{bmatrix}, \qquad v := \begin{bmatrix} v_l \\ v_r \end{bmatrix}$$

This is satisfied for all cases where the output wave amplitude is bounded by the amplitude of the possibly delayed input wave.

Stability: the H_∞ norm of the function mapping input waves into output waves must be least or equal to 1 (small gain theorem)

Scattering – Wave variables

Transformations mapping power variables (force, velocity) into wave variables (input and output waves)

left hand port

$$\begin{cases} u_l = \dfrac{1}{\sqrt{2b}}(F_l + b\dot{x}_l) \\ v_l = \dfrac{1}{\sqrt{2b}}(F_l - b\dot{x}_l) \end{cases} \qquad \begin{cases} u_r = \dfrac{1}{\sqrt{2b}}(F_r - b\dot{x}_r) \\ v_r = \dfrac{1}{\sqrt{2b}}(F_r + b\dot{x}_r) \end{cases}$$

right hand port

where $b > 0$ is the **characteristic impedance** and affects the system behavior. (only the performance, not the stability of the system)
b can be time-varying and state-dependent.

Transformations mapping wave variables (input and output waves) into power variables (force, velocity)

$$\begin{cases} F_l = \sqrt{\dfrac{b}{2}}(u_l + v_l) \\ \dot{x}_l = \dfrac{1}{\sqrt{2b}}(u_l - v_l) \end{cases} \qquad \begin{cases} F_r = \sqrt{\dfrac{b}{2}}(u_r + v_r) \\ \dot{x}_r = -\dfrac{1}{\sqrt{2b}}(u_r - v_r) \end{cases}$$

Each port is also uniquely determined if one wave variable and one power variable are specified.

CASE 1: FORCES

if the left-hand port force F_l and the right-hand port force F_r, are given, the wave transformations are

dep. vars

$$\begin{cases} u_l = \sqrt{\frac{2}{b}} F_l - v_l \\ \dot{x}_l = \frac{1}{b}(F_l - \sqrt{2b}\, v_l) \end{cases} \qquad \begin{cases} u_r = \sqrt{\frac{2}{b}} F_r - v_r \\ \dot{x}_r = -\frac{1}{b}(F_r - \sqrt{2b}\, v_r) \end{cases}$$

CASE 2: VELOCITIES

if the left-hand port velocity $\dot{x}_l$ and the right-hand port velocity $\dot{x}_l$ are given, the wave transformations can be written as

$$\begin{cases} u_l = \sqrt{2b}\, \dot{x}_l + v_l \\ F_l = b\, \dot{x}_l + \sqrt{2b}\, v_l \end{cases} \qquad \begin{cases} u_r = -\sqrt{2b}\, \dot{x}_r + v_r \\ F_r = -b\, \dot{x}_r + \sqrt{2b}\, v_r \end{cases}$$

Each port is also uniquely determined if one wave variable and one power variable are specified.

CASE 3: **MIXED VARIABLES**

it is useful to specify a velocity command at one port ($\dot{x}_l$) and imposing a force command at the other port (F_r)

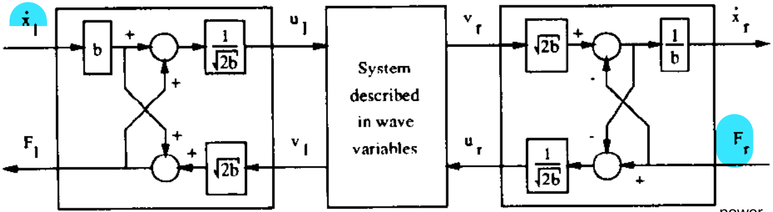
This transformation corresponds to the scheme

F_r, v_r indep var

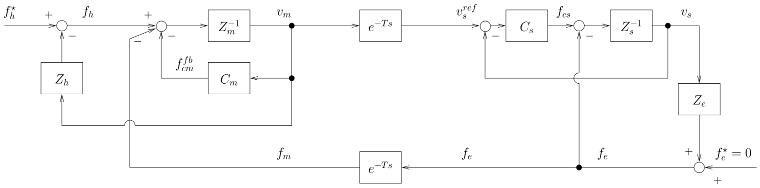
$\dot{x}_l$, v_l indep var

F_l, u_l dep var

$\dot{x}_r$, u_r dep var



Teleoperation with communication delays



Question: where does the instability come from?

$$P = \dot{x}_m(t)F_m(t) - \dot{x}_s(t)F_s(t)$$

Step 1. re-write P as sum/difference of positive terms

from

$$\begin{aligned}(F_m - b\dot{x}_m)^2 &= F_m^2 - 2b\dot{x}_m F_m + b^2\dot{x}_m^2 \\ (F_s + b\dot{x}_s)^2 &= F_s^2 + 2b\dot{x}_s F_s + b^2\dot{x}_s^2\end{aligned}$$

we have

$$P = -\frac{1}{2b}(F_m - b\dot{x}_m)^2 + \frac{1}{2b}F_m^2 + \frac{b}{2}\dot{x}_m^2 - \frac{1}{2b}(F_s + b\dot{x}_s)^2 + \frac{1}{2b}F_s^2 + \frac{b}{2}\dot{x}_s^2$$

Step 2. from

$$\frac{d}{dx}\int_{\alpha(x)}^{\beta(x)} f(t,x)dt = \beta'(x)f(\beta(x),x) - \alpha'(x)f(\alpha(x),x) + \int_{\alpha(x)}^{\beta(x)} \frac{d}{dx}f(t,x)dt$$

and using

$$\begin{aligned} \dot{x}_s(t) &= \dot{x}_m(t-T) \\ F_m(t) &= F_s(t-T) \end{aligned}$$

we end up with

$$\begin{aligned} P &= -\frac{1}{2b}(F_m(t) - b\dot{x}_m(t))^2 + \frac{1}{b}F_m^2(t) - \frac{1}{2b}(F_s(t) + b\dot{x}_s(t))^2 + b\dot{x}_s^2(t) + \\ &+ \frac{d}{dt}\int_{t-T}^{t}\left[\frac{b}{2}\dot{x}_m^2(s) + \frac{1}{2b}F_s^2(s)\right] ds \end{aligned}$$

$$P = \underbrace{-\frac{1}{2b}(F_m(t) - b\dot{x}_m(t))^2 + \frac{1}{b}F_m^2(t) - \frac{1}{2b}(F_s(t) + b\dot{x}_s(t))^2 + b\dot{x}_s^2(t)}_{\text{power dissipation } P_{diss}} +$$

$$+\frac{d}{dt}\underbrace{\int_{t-T}^{t}\left[\frac{b}{2}\dot{x}_m^2(s) + \frac{1}{2b}F_s^2(s)\right]ds}_{\text{stored energy } E}$$

sempre >= 0

E(t) >= 0 per ogni t

in the stored energy appear the input variables

$\dot{x}_m$, F_s

The rate of change of stored energy is then

$$\frac{dE}{dt} = P - P_{diss}$$

$$P = \frac{dE}{dt} + P_{diss}$$

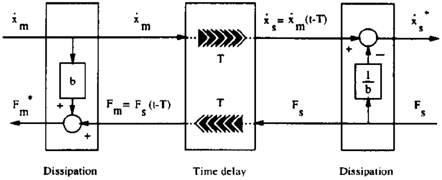
a system is passive if Pdiss >= 0

IMPORTANT

Some values for the input variables $\dot{x}_m$ and F_s can make $P_{diss} < 0$!!!

=> the delay element introduces the possibility of instability

Dissipating elements



The dissipative blocks can be seen as viscous friction (located next to the communication block to be independent of the T and the elements of the system)

Modified power flow:

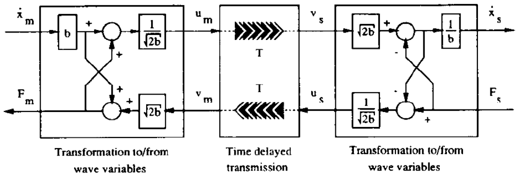
$$P = \underbrace{\frac{1}{2b}(F_m^\star(t))^2 + \frac{b}{2}(\dot{x}_s^\star(t))^2}_{\text{power dissipation } P_{diss}} + \frac{d}{dt}\underbrace{\int_{t-T}^{t}\left[\frac{b}{2}\dot{x}_m^2(s) + \frac{1}{2b}F_s^2(s)\right] ds}_{\text{stored energy } E}$$

with $P_{diss} \geq 0$. In particular $P_{diss} > 0$ any time $F_m^\star(t) \neq 0$ or $\dot{x}_s^\star(t) \neq 0$

Drawbacks:

- the slave does not converge to the master position (velocity control!)
- a continuous power input is required to sustain a constant force reflection/motion

Idea: transmit the wave variables instead of the power variables



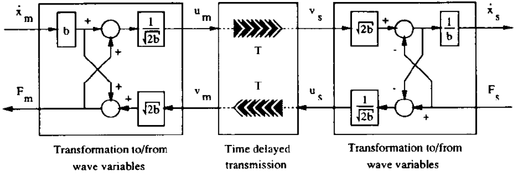
Power flow

$$
\begin{aligned}
P &= \frac{1}{2}u_m^2(t) - \frac{1}{2}v_m^2(t) + \frac{1}{2}u_s^2(t) - \frac{1}{2}v_s^2(t) \\
&= \frac{1}{2}u_m^2(t) - \frac{1}{2}u_s^2(t-T) + \frac{1}{2}u_s^2(t) - \frac{1}{2}u_m^2(t-T) \\
&= \frac{d}{dt}\underbrace{\int_{t-T}^{t}\left[\frac{1}{2}u_m^2(s) + \frac{1}{2}u_s^2(s)\right]ds}_{\text{stored energy } E}
\end{aligned}
$$

Properties:

- $P_{diss} = 0$ (lossless!!!) nothing is dissipated, but nothing is generated => passive!
- independent of T the only assumption is that the delay is constant

Idea: transmit the wave variables instead of the power variables



We have

$$
\begin{aligned}
F_m(t) &= F_s(t-T) + b\left(\dot{x}_m(t) - \dot{x}_s(t-T)\right) \\
\dot{x}_s(t) &= \dot{x}_m(t-T) - \frac{1}{b}\left(F_s(t) - F_m(t-T)\right)
\end{aligned}
$$

Remark: when $T = 0$, transmitting wave variables is the same to transmit power variables!!!

Exercise

Implement the scattering transformation and analyze the system behavior for different values of b and for different (constant) delays T.

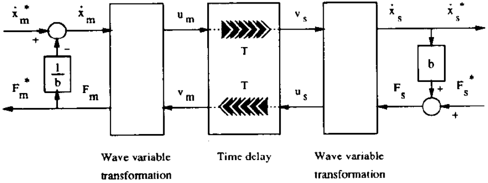
Matching the wave impedance

Physics: waves are reflected at junctions and terminations, i.e. where the impedance of the wave carrier changes.

In a teleoperation scenario, reflections occur at the slave and master side (the impedance *b* of the wave transmission).

Solution: inserting termination elements to match impedance.

Otherwise: vibrations



$$\dot{x}_m = \dot{x}_m^* - \frac{1}{b} F_m, \qquad F_s = F_s^* + b\dot{x}_s,$$

Matching the wave impedance

With these terminators, we end up with (master m in place of left l, slave s in place of right r)

$$\begin{cases} u_m = \sqrt{\frac{b}{2}}\dot{x}_m^* \\ F_m = \frac{b}{2}\dot{x}_m^* + \sqrt{\frac{b}{2}}v_m \end{cases} \qquad \begin{cases} u_s = \frac{1}{\sqrt{2b}}F_s^* \\ \dot{x}_s = -\frac{1}{2b}F_s^* + \frac{1}{\sqrt{2b}}v_s \end{cases}$$

i.e., u_m does not depend on v_m, and u_s does not depend on v_s,

Problem: termination elements introduce scaling in force (master side) and velocity (slave side)

$$\begin{aligned} F_m(t) &= \frac{1}{2}F_s^*(t-T) + \frac{b}{2}\dot{x}_m^*(t) \\ \dot{x}_s(t) &= \frac{1}{2}\dot{x}_m^*(t-T) - \frac{1}{2b}F_s^*(t) \end{aligned}$$

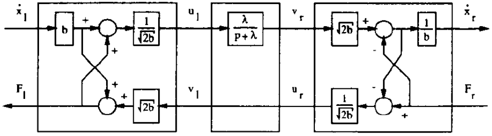
Exercise

Insert the termination elements and evaluate the entity of the velocity scaling (position drift).

Wave filtering

Question: How is it possible to introduce a (low-pass) filter in a passive way?

Answer: using the scattering transformation (again!)



In this case the filtered signal is the wave variable and not the power variable (ex. velocity): in the forward or backward path, or in both!

The transfer function

$$F(s) = \frac{\lambda}{p+\lambda}, \qquad \lambda > 0$$

implies

$$\dot{v}_r(t) + \lambda v_r(t) = \lambda u_l$$

Then, the power flow becomes

$$P = \frac{1}{2}u_l^T u_l - \frac{1}{2}v_l^T v_l + \frac{1}{2}u_r^T u_r - \frac{1}{2}v_r^T v_r = \frac{1}{2\lambda^2}\dot{v}_r^T \dot{v}_r + \frac{d}{dt}\left(\frac{1}{2\lambda}v_r^T v_r\right)$$


Project

PROJECT – Assignment # 6

ultimi 5 minuti 5 dicembre

To do

- Implement the Scattering-based bilateral teleoperation architecture for the
  1. Force-Position case
  2. Position-Position case
- Compare positions, velocities, forces, commands in free motion and in contact
- Create another simulink model and (a) add the measurement noise to the position/force signals, and (b) estimate velocities from positions