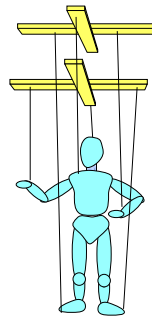


*Robotic Telem Manipulation:
General Aspects and Control Aspects*

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Telem Manipulation

Summary:

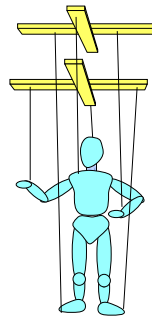
1. Introduction;
2. General description of a telem Manipulation system;
3. Overview on applications and existing devices;
4. Force reflection in telem Manipulation;
5. Introduction to the Passivity Theory;
6. Modelling of telem Manipulation systems;
7. Control techniques for telem Manipulation systems;
8. Performance measures for telem Manipulation systems;
9. Demos (experimental setup).

*Robotic Telemanipulation:
Introduction - History - Applications*

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Telemanipulation - Introduction

Development of different “TELE-technologies”:

- **TELE**graphy;
- **TELE**phony;
- **TELE**vision;
- ...
- **TELE**operation:
capability of performing remote manipulation of objects/environments.

Teleoperations is one of the first fields in robotics to be developed:

⇒ applications (nuclear, medicine) are dated back to the late 40's.

Probably, the initial noticeable research interest, despite the existing operating devices, has not been fully respected:

- technological reasons;
- different location of the operator and robotic device.

Telemanipulation - Introduction

Some basic definitions:

HUMAN OPERATOR: person performing the observation and control (supervision of the development) of a desired task.

TELEOPERATOR: machine that extends (to a remote location) the sensing and manipulation capabilities of an human operator.

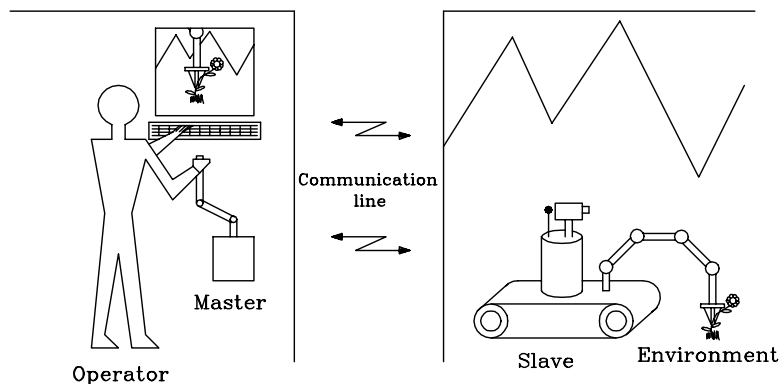
TELEROBOT: advanced form of teleoperator, usually supervised by an human operator by means of a control systems.

General description of a telemanipulation system

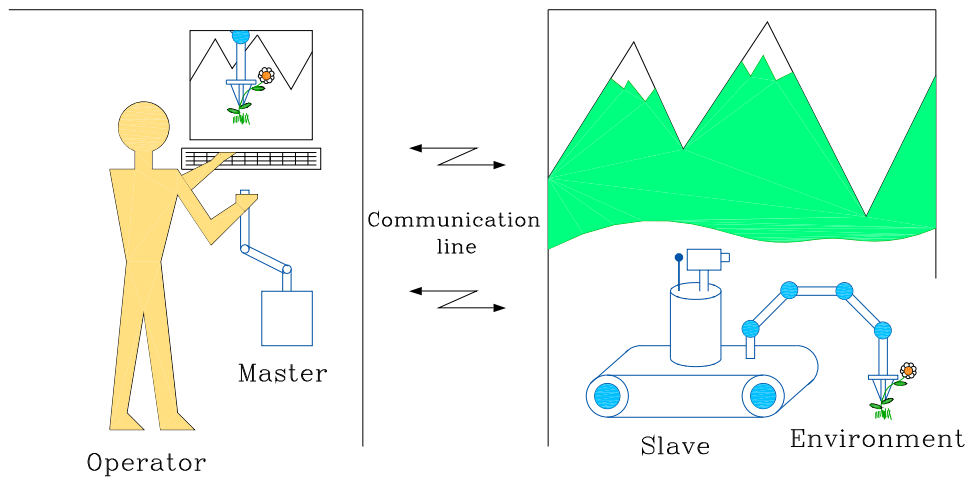
In current terminology, a telemanipulator is a complex electro-mechanical system usually encompassing:

- a *master* (or local) device,
- a *slave* (or remote) device,
- a *communication channel*, interconnecting the master and the slave.

The overall system is interfaced on one side (the master) with a human operator, and on the other (the slave) with the environment.



General description of a telemanipulation system



Both master and slave devices have their own local control system, with a very large variety of complexity and sophistication levels, which allow the execution of desired tasks.

General description of a telemanipulation system

There are some features of this kind of manipulators which are not present in an “usual” robotic manipulation system.

1. A human operator is present for the high-level control of the activities.
2. Since the operator represents the main “controller” of the system, he/she requires to be informed about the evolution of the task and about some pertinent information:
 - data feedback from the slave site to the master one,
 - development of a proper user interface.

Signals fed back to the master may be related to

- forces applied to the environment,
 - relevant positions of the slave,
 - graphical video data,
 - tactile or acoustic information,
 - ...
3. A communication channel is present between the master and the slave sites.

This channel may represent a source of problems when a time-delay is present, since, as well known from the control theory, delays in a feedback loop may generate instability.
Even time-delays of the order of the tenth of a second may create instability problems.

General description of a telemanipulation system

The main features of the components of a telemanipulator are the following.

The master.

The master, or local system, is the interface through which the operator specifies commands to the whole device. Typical features of the master are:

- Capability of **assigning tasks to the slave** and **providing the operator with relevant information** about the task development.

“TELEPRESENCE”

Several implementative solutions have been adopted: joysticks and/or consoles, exoskeletons, ...

Different types of signals may be reflected by these devices to the operator, from simple graphical data to full kinetostatic information.

- Capability of **acquiring and processing data** from both the operator and the slave. Typical elaborations are filtering, prediction, delay compensation, modelling of remote and local dynamics, and so on.

General description of a telemanipulation system

The slave.

The slave is the part of the teleoperator which directly interacts with the environment for task execution. Requirements similar to the master may be specified for the slave system:

- A **robotic system** for the interaction with the environment and the execution of the task planned by the operator.
This part, usually provided with autonomous features, has to be in some way customised to operate in particular environments, e.g. submarine, outer space, nuclear areas.
Note that the kinematics and the dynamics of the remote manipulator may be different from those of the local one (problems when telepresence is needed).
- A **signal acquisition and processing**.
Sensory capability is a main requirement for the slave device, which is often equipped with video cameras, force/tactile sensors, proximity sensors, and so on.
- The **capability of data processing**. Also the remote site must be able to elaborate the information needed for task execution. In fact, besides other considerations, the destabilising effects originated by communication delays and/or restricted bandwidths of transmission must be compensated locally, providing the slave system with a certain degree of autonomy.

General description of a telemanipulation system

The communication line.

The communication line represents the link between the master and slave sites. Different platforms may be used for this purpose, from radio connections by means of satellites to cables for underwater operations.

Main drawback. Time delay in the transmission of signals:

- physical delay in the transmission line (e.g. in a long satellite communication),
- limited bandwidth of the hardware.

The time delay, **in some case not constant**, can originate noticeable instability problems if proper compensating actions are not taken.

General description of a telemanipulation system

The communication line.

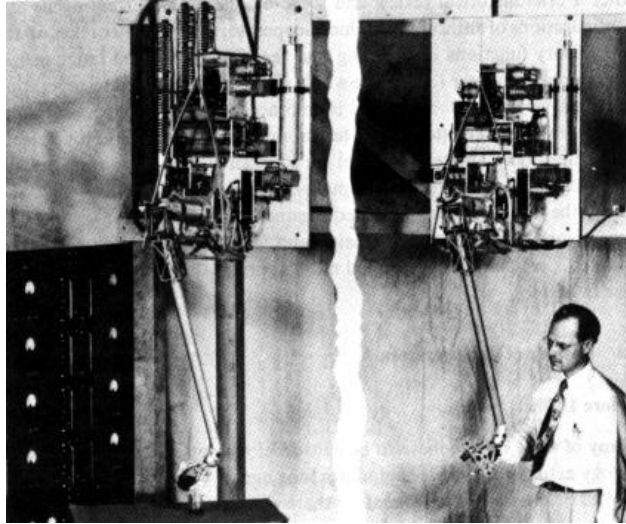
A very common choice in practical applications is to transmit velocity to the slave and force to the master (for the *kinestatical coupling*).

Obviously, the choice of reflecting forces is not the only possible. For example, 3D graphic simulation could be used as well. Nevertheless, coordination based on force greatly improves the execution of tasks with respect to the case of, for example, only visual feedback.

Anyway, the transmission of force information originates **relevant instability problems when time-delays are present** in the communication line (problem noticed since the first implementation of telemanipulation schemes with force reflection in 1965).

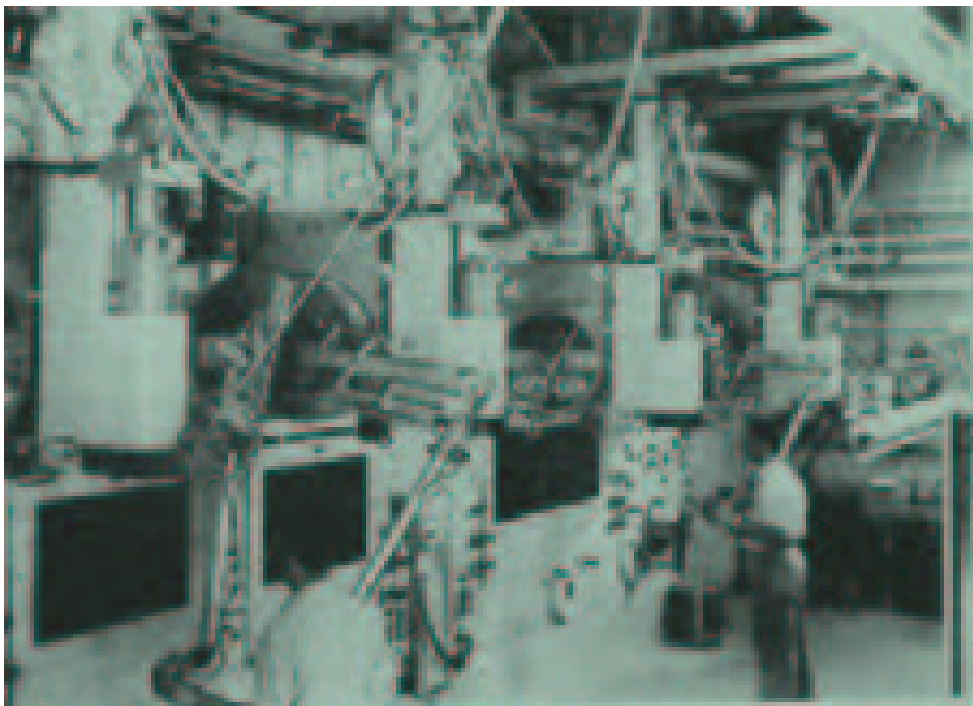
Overview on applications

- < 1600: very simple devices designed as arm extensions;
- early 1900: crude teleoperators for earth moving, constructions, and related tasks;
- '40s: human limb prostheses (arm hooks activated by the parts of the human body);
- about 1945: first master-slave teleoperator (mechanical pantograph) for radioactive material manipulation;



Development of Telemanipulation

- 1954: electro-mechanical master-slave teleoperator developed by Goertz at Argonne National Lab.;



Development of Telemanipulation

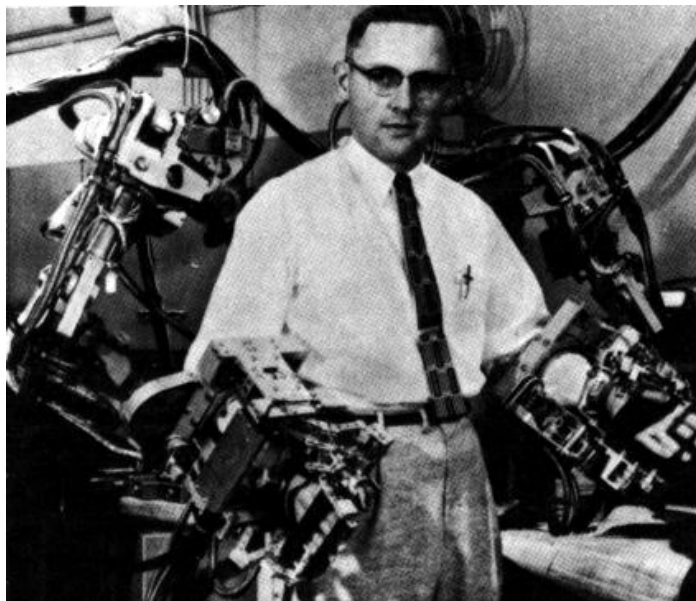
late 50's interest in applying this new technology to human limb prostheses. Koblinski (Moscow) in 1960 developed a lower-arm prosthesis driven by myoelectric signal from the upper arm;

60's Rapid developments in the medical field, with teleoperators installed on the wheelchairs of quadriplegics and commanded by the tongue;



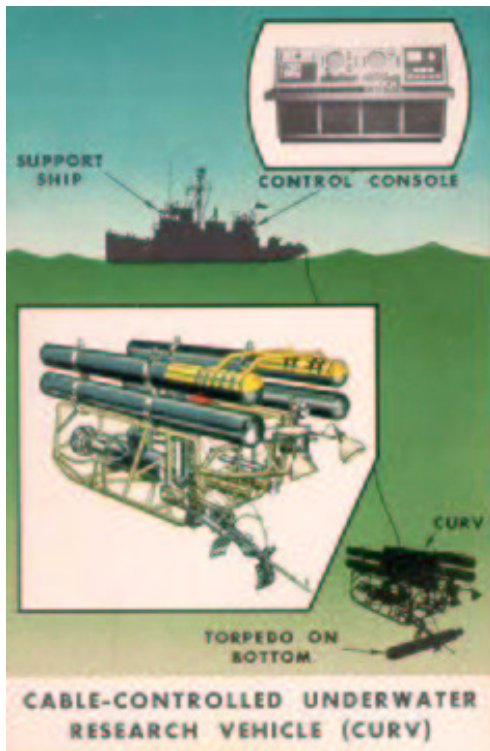
Development of Telemanipulation

60's: Telepresence, force reflection, two-arm teleoperators. touch sensing and display, Significant example is the Mosher's Handyman, developed at General Electric Co.;



Development of Telemanipulation

1966: US Navy's CURV (Cable Controlled Underwater Vehicle), for retrieval of a bomb from the deep ocean.



Development of Telemanipulation

1965: first experiments with relevant time-delays (race to the Moon): instability problems were firstly noticed in force reflection.



Figure 2.7

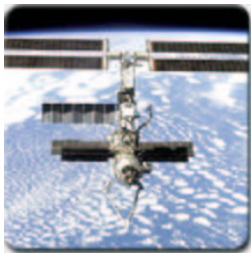
Overview on applications

Use of telemanipulators, in the broader sense of the terminology, may be found in a number of different areas developed since the early 50's. First examples of these devices have been designed and realised for operations in radioactive environments and for human limb prostheses.

At the moment, this technology is applied in a number of different fields:

- space,
- underwater,
- medicine,
- hazardous environments,
- production,
- security,
- simulators,
- ...

Space applications



Robots are used in space for:

- exploration,
- scientific experiments,
- commercial activities.

Main reasons of using robots in space are

- high costs of human operators,
- hostile environment for human beings.

At the moment, most part of the teleoperation in space is performed in activities related to shuttles (problems are well defined and the environment is structured).

Usually, the operator performs a direct control of the task executed by the manipulator.

Main directions of current research activity are the development of:

- arms for intra-vehicular and extra-vehicular activities (ESA, NASA, ...),
- free flying platforms,
- planetary rovers.

The Canadian Remote Manipulator System - RMS

The arm installed on the US space-shuttle, the Canadian Remote Manipulator System (RMS), is probably the most known example of space telemanipulator:

- built by the Canadian firm MD robotics
- 6 dof arm
- 20 meter long flexible structure
- able of executing pre-programmed and/or teleoperated tasks
- resolved rate control

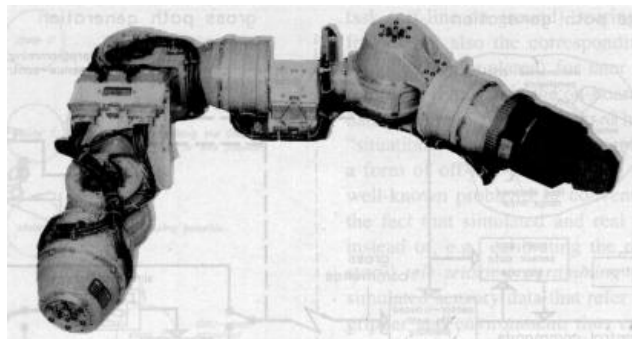


Rotex

ROTEX is a robotic arm for intra-vehicular activities developed by DLR, Germany. It was successfully used in the mission of the space-shuttle COLUMBIA in 1993, performing three significant tasks: assembly of a grid, connection/disconnection of an electrical plug, grasp of a flying object.

Main features:

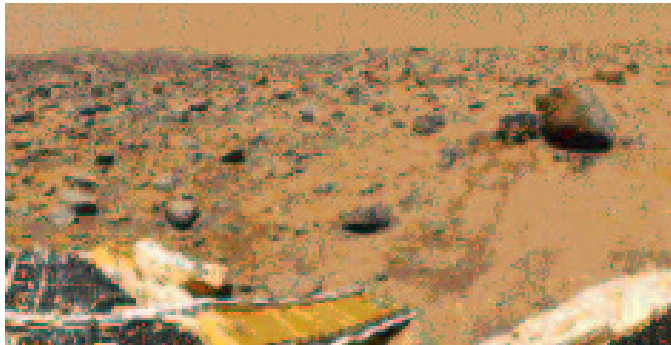
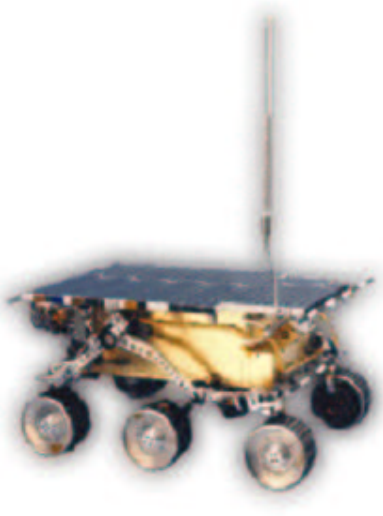
- 6 dof, light structure
- advanced materials
- complex sensorial system:
 - two 6-axis force/torque sensors,
 - tactile arrays,
 - an array of 9 laser rang-finders,
 - a pair of tiny video-cameras for a stereo image of the grasping area.
- a rather sophisticated man-machine interface exploiting 3D stereo computer graphics, voice input/output, stereo imaging
- predictive control
- the master system is the "DLR control-ball" (6-axis force sensor)



Space rovers

A successful space telerobotic program has been the Mars Viking Program, which performed scientific experiments on the Martian surface.

The rover **Sojourner** is probably the most known space rover, after the successful NASA mission Pathfinder on Mars (July 4, 1997).



Space rovers

Current technology would allow further substantial developments, which are slowed down by the large amount of money and time required to guarantee a successful mission.

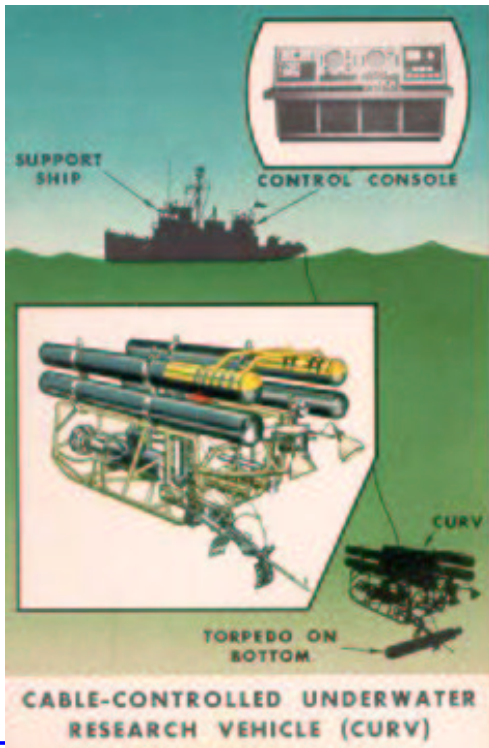
For these reasons the research are in general jointly developed by national space agencies, industries and research laboratories.

Relevant technical problems still exist due to:

- reliability requirements,
- weight constraints,
- hostile environments
- communication time-delays
(from 1 second in earth orbits to 4-40 minutes for planetary missions).

Underwater

1966: first successful military applications of underwater telemanipulators; the U.S. Navy's CURV was successfully employed to retrieve a nuclear bomb from the ocean.

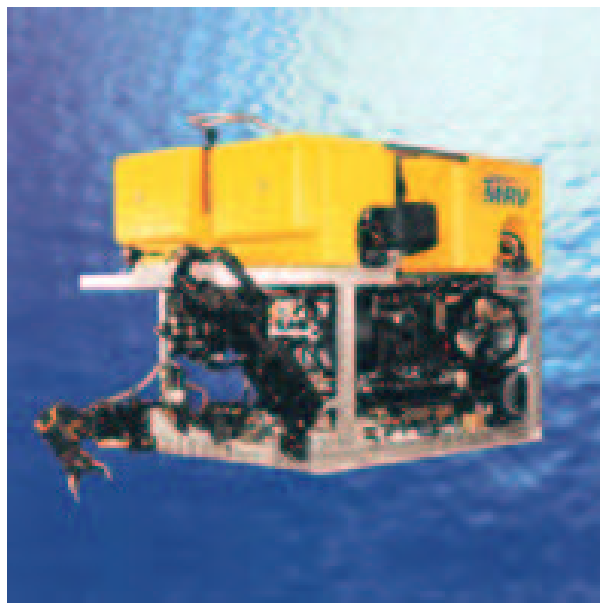


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Underwater

80's: extensive use of ROVs (Remote Operated Vehicles) for offshore operations for oil/gas industry.



At the moment, underwater telerobotics is mainly used for business, military missions and scientific expeditions.

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Underwater

Use:

- The main users of telesubmersibles are the communications (telephone) and oil industries, where under water pipes and cables require routine operations.
- The scientific community uses this technology for marine biological, geological, and archaeological missions.
- The military have used telerobotics in many salvage operations, such as plane or watercraft recovery.

However, the most important users are probably in the business field, where it is more economical to send teleoperated devices rather than human divers.

Technical problems due to conditions of the water environment:

- high pressures ⇒ hydraulic actuators
- poor visibility ⇒ External lighting, sonar, ...
- communication difficulties ⇒ radio, cables, (both), ...

Underwater

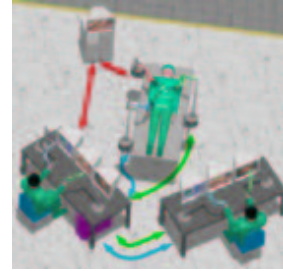
Control aspects:

- first examples of underwater teleoperation were mainly based on manned submersibles, either free swimming or connected to a surface ship, and with teleoperated arms on the outer structure;
- telerobotics (autonomous) tasks are usually limited to small routine tasks rather than complete activities, for example simple tool switching operations, repetitive bolt/nut screwing, piloting to new locations;
- in more recent operations, human operators remotely control the submersibles;
- computer graphic simulation may help the user during task execution in partially known environments.

Medicine (Telesurgery)

Main applications of robotic manipulators in the medical field:

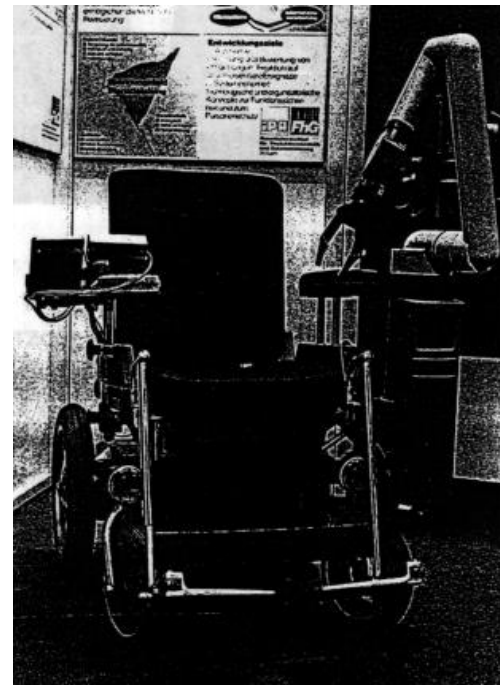
- help to impaired people,
- surgery operations,
- diagnose illnesses or injuries,
- training of specialised personnel.



Medicine (Telesurgery)

Robotic systems of different complexities have been developed since the 50's for helping impaired people.

Among the most common systems are automated wheelchairs, controlled by voice or by joysticks for hands, mouth, eye or head movements.



Medicine (Telesurgery)

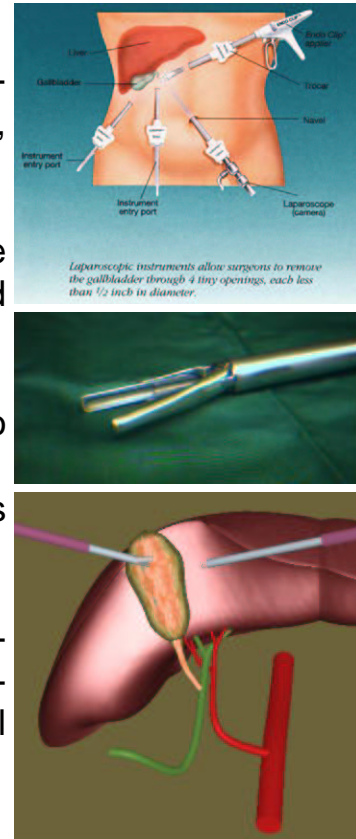
At the moment, there is a relevant interest in applying teleoperated devices in microsurgery operations, e.g. eye surgery, where small precise movements are needed.

The movements of the operator are scaled down by the mechanism so that very fine operations can be performed while maintaining a suitable telepresence effect.

Another important class of surgical process consists of the so called “minimally invasive” procedures.

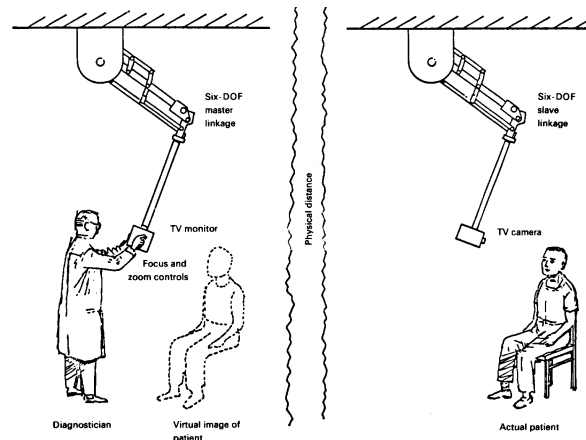
In this case, the surgeon operates through small insertions using thin medical instruments and small video cameras.

The increased difficulties for the surgeon are partially compensated by computers, which are used to create virtual environments where the use of telepresence plays a fundamental role.



Medicine (Telesurgery)

Telediagnosis may also broaden the range of a single doctor by allowing to exam a patient visually or viewing records on a computer interface.



Telemanipulation may be used in surgery operations for

- remote surgery (militar, ...)
- improving performances for operation presenting spatial problems for a surgeon (better and less destructive results)
- improving reach, manipulation, sight and insight on the patient body

Finally, telepresence is becoming very important for the instruction of specialised doctors and for performing rehearsals before the actual operation.

Telerobotics in hazardous environments

Nuclear industry was the first important user of modern teleoperating devices.



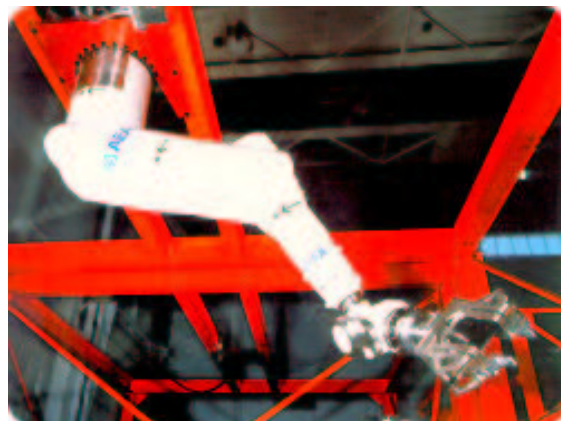
Telerobotics is applied in hazardous environments (nuclear, chemical, military applications) for a variety of tasks:

- direct handling of radioactive or chemical material,
- waste cleanup/disposal
- plant inspection
- ammunition disposal
- ...

Telerobotics in hazardous environments

The scenario ranges from very specialised machines (e.g. handling nuclear or chemical material) which usually only require human supervision to fully teleoperated devices (in cleanup operations where the environment is usually less structured).

- Reliability is one of the main requirements, since equipment must typically operate in contaminated/dangerous areas for long periods of time.
- Significant technological problems are encountered due to radiations and high temperatures.



Telerobotics in mining and other industries

Besides the typical use of robots in a number of industrial applications (assembly, welding, painting, and so on), other applications of robotic systems in 'non-conventional' production processes have been developed, for example in:

- mines,
- constructions,
- agriculture,
- warehousing,
- security,
- ...



Other applications of telerobotics

- **Augmented reality and stereo vision.**

Augmented reality means to enhance the data given to the operator, trying to provide him/her with more complete and general information of those obtainable directly.

Besides the visual data that can be normally observed, these information also include any form of data that increases the user perception of the environment, including pre-processing of the video scenes, use of active and/or stereo vision, graphical images, and virtual tools.

- **Security.**

Applications in this area aim to employ telerobotic devices for the protection of persons and properties. Most systems used in this area are teleoperated devices since these tasks require decision capabilities and intelligence levels not possible for machines at the present time.

In the area of security, robots may be used for patrolling buildings (e.g. offices and factories) and for protection purposes.

Also militars adopt teleoperation, mainly for locating enemies or dangerous equipment without direct risk for human personnel.

- **Training and simulators in telerobotics.**

Some industries have been using this technology for many years. Perhaps, the most popular examples are the flight simulators, used to train pilots.

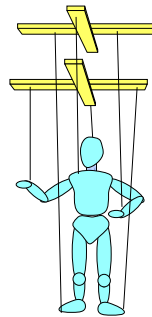
The goals are to give to human operators expertise about complex activities, in reduced time, with lower costs and minor risk of injury.

Robotic Telemanipulation: Passivity Theory

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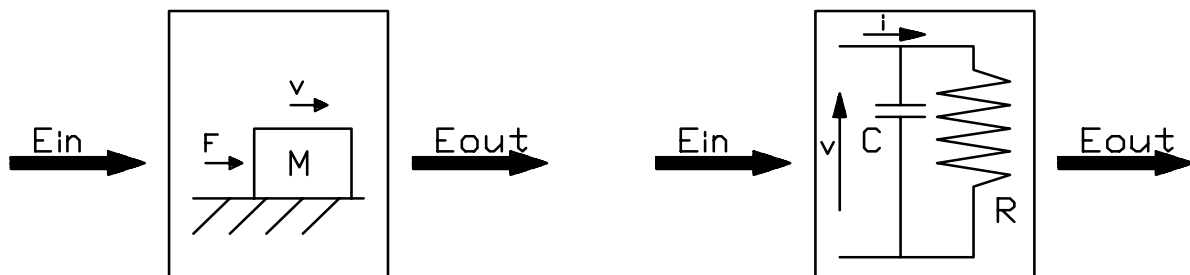


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Passivity Theory

Passivity:

- represents a powerful and elegant tool for the analysis and control design for both linear and non linear dynamic systems;
- is a mathematical description of the physical concepts of power and energy;
- is very closely related to the stability theory (Lyapunov, energy functions);
- allows the design of control strategies for the interaction with arbitrary passive environments without too concern on modelling and estimation;
- human operators can easily deal with passive systems;
- transient phases are not well described.



Passivity: some definitions

Let us introduce the following notations:

- \mathcal{T} , a subset of \mathbf{R}_+ (in general the time domain);
- \mathcal{V} , a vector space with the usual Euclidean norm $\|\cdot\|$ (usually \mathbf{R}^n);
- \mathcal{F} , the set of all functions mapping \mathcal{T} in \mathcal{V} : $\{\mathbf{f} : \mathcal{T} \mapsto \mathcal{V}\}$, with the properties of a linear space;

and the *causal truncation* operator (defined in the case of infinite time functions)

$$P_T \mathbf{f}(t) = \begin{cases} \mathbf{f}(t) & t \leq T \\ \mathbf{0} & t > T \end{cases} \quad \mathbf{f}(t) \in \mathcal{F}, \quad t, T \in \mathcal{T}$$

Passivity: some definitions

Moreover, let us consider:

1. the normed linear subspace, \mathcal{L}_2^n , of the linear space \mathcal{F} (the Hilbert space of the functions measurable in the Lebesgue sense):

$$\mathcal{L}_2^n(\mathcal{T}) = \left\{ \mathbf{f} : \mathcal{T} \mapsto \mathcal{V}, \left(\int_0^\infty \|\mathbf{f}\|^2 dt \right)^{1/2} < \infty \right\}$$

2. the extended space \mathcal{L}_{2e}^n associated to \mathcal{L}_2^n :

$$\mathcal{L}_{2e}^n(\mathcal{T}) = \{\mathbf{f}(t) : P_T \mathbf{f}(t) \in \mathcal{L}_2^n(\mathcal{T})\}$$

$\mathcal{L}_{2e}^n(\mathcal{T})$ is the space of functions whose causal truncation belongs to $\mathcal{L}_2^n(\mathcal{T})$.

Passivity: some definitions

Moreover:

- $\forall \mathbf{f} \in \mathcal{L}_{2e}^n(\mathcal{T})$, the map $T \mapsto \|P_T \mathbf{f}\|$ is monotonically increasing,
- $\forall \mathbf{f} \in \mathcal{L}_2^n(\mathcal{T})$, the map $\|P_T \mathbf{f}\| \mapsto \|\mathbf{f}\|$ as $T \mapsto \infty$.

Consider a dynamic system described in the space state as

$$\begin{cases} \dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t)) + \mathbf{g}(\mathbf{x}(t))\mathbf{u}(t) \\ \mathbf{y}(t) = \mathbf{h}(\mathbf{x}(t)) \end{cases} \quad (1)$$

where $\mathbf{x} \in \mathcal{L}_{2e}^n(\mathcal{T})$, $\mathbf{y} \in \mathcal{L}_{2e}^m(\mathcal{T})$, $\mathbf{u} \in \mathcal{L}_{2e}^m(\mathcal{T})$. Assume the functions \mathbf{f} , \mathbf{g} , \mathbf{h} smooth in \mathbf{x} , with $\mathbf{f}(\mathbf{0}) = \mathbf{0}$, $\mathbf{h}(\mathbf{0}) = \mathbf{0}$.

Passivity: some definitions

A function $w(t)$, called *SUPPLY RATE*, of the input $\mathbf{u}(t)$ and of the output $\mathbf{y}(t)$ is defined as

$$w(t) = w(\mathbf{u}(t), \mathbf{y}(t))$$

The function $w(t)$ is assumed to be locally integrable, i.e.

$$\int_{t_0}^{t_1} \|w(t)\| dt < \infty, \quad \forall t_0, t_1 \in \mathbf{R}_+$$

In the following, this function is assumed of the form

$$w(t) = \mathbf{y}^T(t)\mathbf{u}(t)$$

Passivity: some definitions

Definition: The system (1) is said to be **PASSIVE** if there exists a continuous function, called **storage function**, $V(\mathbf{x}) \geq 0$, $V : \mathcal{L}_{2e}^n(\mathcal{T}) \rightarrow \mathbf{R}_+$, which satisfies $V(\mathbf{0}) = 0$, such that

$$\int_{t_0}^t \mathbf{y}^T(\tau) \mathbf{u}(\tau) d\tau \geq V(\mathbf{x}(t)) - V(\mathbf{x}(t_0)) \quad (2)$$

Definition: The system (1) is said to be **STRICTLY PASSIVE** if there exists a continuous (storage) function, $V(\mathbf{x}) \geq 0$, $V : \mathcal{L}_{2e}^n(\mathcal{T}) \rightarrow \mathbf{R}_+$, which satisfies $V(\mathbf{0}) = 0$, and a positive definite function, called **dissipation rate**, $\phi(\mathbf{x}(t))$, $\phi > 0$, $\phi : \mathcal{L}_{2e}^n(\mathcal{T}) \rightarrow \mathbf{R}_+$ such that

$$\int_{t_0}^t \mathbf{y}^T(\tau) \mathbf{u}(\tau) d\tau \geq V(\mathbf{x}(t)) - V(\mathbf{x}(t_0)) + \int_{t_0}^t \phi(\mathbf{x}(\tau)) d\tau \quad (3)$$

Passivity: some definitions

The definition of passivity given in eq. (2) is often reported in the literature in the differential form as

$$\dot{V}(\mathbf{x}(t)) \leq \mathbf{y}^T(t) \mathbf{u}(t)$$

or, by explicitly introducing the dissipation rate function ϕ , as

$$\dot{V}(\mathbf{x}(t)) = \mathbf{y}^T(t) \mathbf{u}(t) - \phi(\mathbf{x}(t)) \quad (4)$$

which reflects the concept of the conservation of energy of a physical system. As previously mentioned, passivity and Lyapunov stability are closely related concepts. In fact, the following result holds.

Lemma Let suppose the system (1) be (strictly) passive. If the storage function $V(\mathbf{x})$ is positive definite, radially unbounded, and decrescent, then, for $\mathbf{u} \equiv \mathbf{0}$, the equilibrium $\mathbf{x} = \mathbf{0}$ of (1) is globally uniformly (asymptotically) stable.

Passivity: some useful properties

1. The passivity formalism may be easily applied to the analysis of stability properties of composed systems.
For example:
 - a combination of passive subsystems is passive,
 - if at least one subsystem is dissipative, then the overall combination is asymptotically stable.
2. If a system with input $\mathbf{u}(t)$ and output $\mathbf{y}(t)$ is passive, then a linear transformation given by a mapping $\mathbf{A}\mathbf{u} \rightarrow \mathbf{A}^{-T}\mathbf{y}$ yields a passive system.
3. More in general, the passivity of a system is not changed by a transformation expressed by an orthogonal matrix \mathbf{A} (i.e. a matrix such that $\mathbf{A}\mathbf{A}^T = \mathbf{I}$).

Passivity concepts have been widely used in robotics:

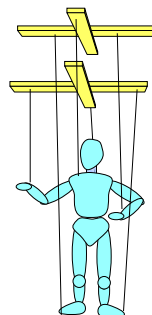
- to study the stability properties of robots interacting with unknown environments,
- for the robustness analysis of force control schemes,
- for the development of *haptic devices*,
- for the design of *telemanipulation control systems*.

Robotic Telemanipulation: Modelling Aspects

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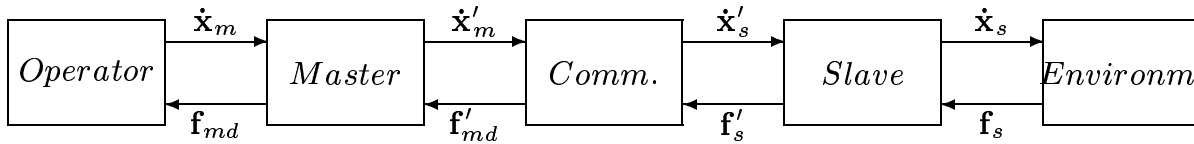


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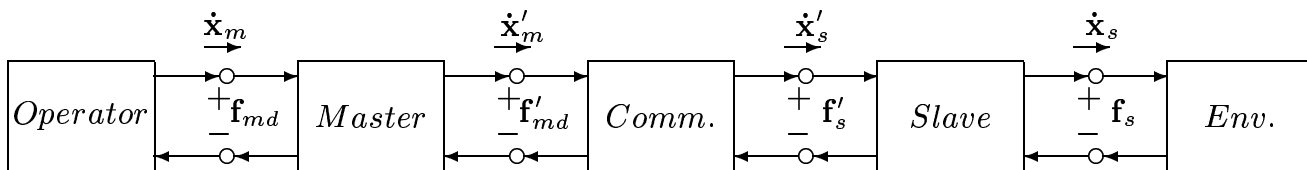


Modelling a teleoperation system

Network analogy: bilateral teleoperation systems can be viewed as a cascade interconnection of two-port (master, communication channel and slave) and one-port (operator and environment) blocks.



By means of the mechanical/electrical analogy and of network theory, the teleoperation system is described as interconnection of one and two-port electrical elements.



Modelling a teleoperation system

Linear Time-Invariant (LTI) continuous systems can be described by the relationships between the effort and flow variables:

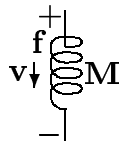
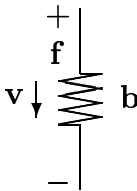
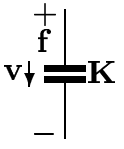
	effort variable	flow variable
mechanical system	force/torque applied to the system	linear/angular velocity of the system
electrical system	voltage across the terminals	current through the network

The analogy is based on similarities between the following variables of mechanical and electrical systems:

Electrical		↔	Mechanical	
Voltage	$V(t)$		Force	$f(t)$
Current	$I(t)$		Velocity	$\dot{x}(t)$
Resistance	R		Viscous friction	b
Inductance	L		Inertia	M
Capacitance	$1/K$		Stiffness	$f(t) = 1/K \int v(t)dt$
One-port impedance	Z		Series/parallel of previous elements	$f(s) = Z(s) v(s)$

Modelling a teleoperation system

Complex mechanical systems can be described by means of elementary mechanical elements (both passive and active):

Inertia M	
Viscous friction b	
Stiffness K	

Two important elements

1. **Two-port ideal transformer:** it models a gear reduction with gain B , and relates forces and velocities as:

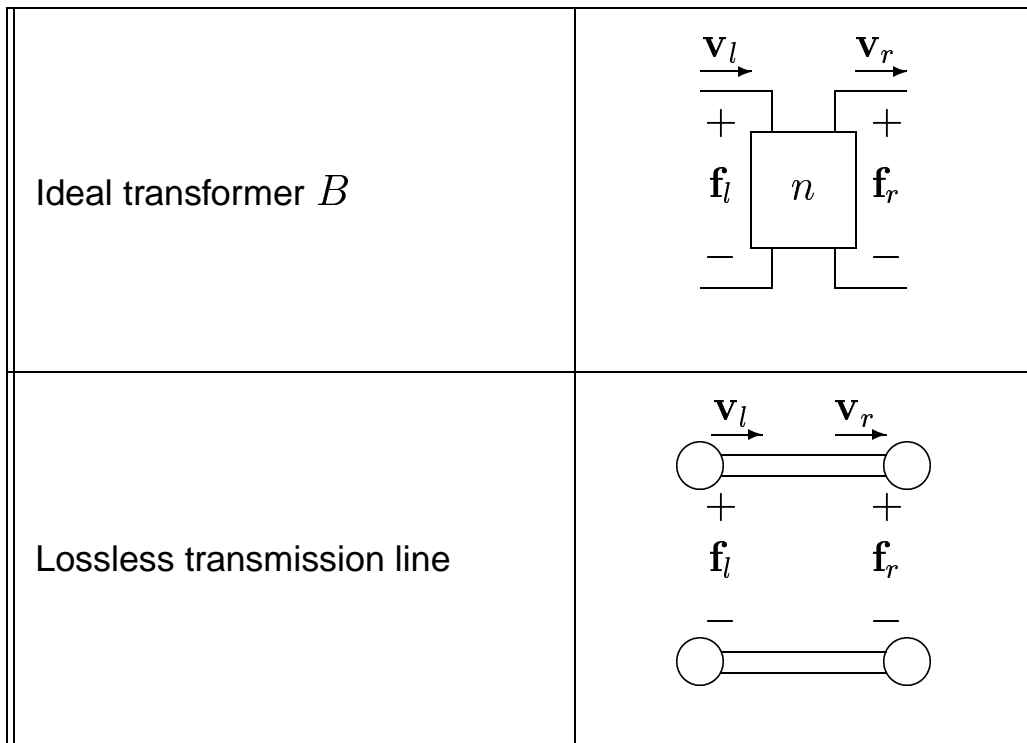
$$f_m(t) = B f_s(t), \quad \dot{x}_m(t) = \dot{x}_s(t) / B$$

2. **Two-port lossless transmission line:** the input/output relationship in the frequency domain is given by:

$$\begin{cases} f_m(s) = Z_0 \tanh(sl/v_0) \dot{x}_m(s) + \operatorname{sech}(sl/v_0) f_s(s) \\ -\dot{x}_s(s) = -\operatorname{sech}(sl/v_0) \dot{x}_m(s) + [\tanh(sl/v_0)/Z_0] f_s(s) \end{cases}$$

where l is the length of the line, $Z_0 = \sqrt{L/C}$, and $v_0 = 1/\sqrt{LC}$ (L and C characteristic inductance and capacitance of the line)

Two important elements



Example of a teleoperation model

Let consider the following master/slave teleoperation device:

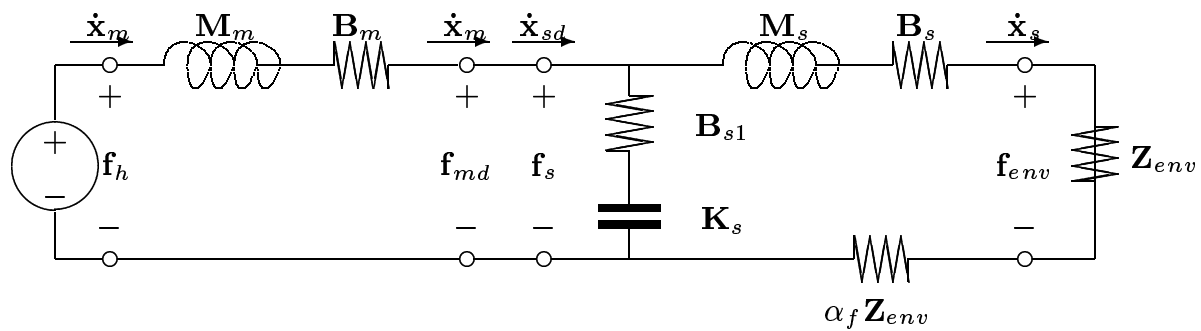
$$\left\{ \begin{array}{ll}
 \mathbf{M}_m \ddot{\mathbf{x}}_m(t) & = \mathbf{f}_h(t) + \boldsymbol{\tau}_m(t) & \text{master dynamics} \\
 \mathbf{M}_s \ddot{\mathbf{x}}_s(t) & = -\mathbf{f}_{env}(t) + \boldsymbol{\tau}_s(t) & \text{slave dynamics} \\
 \boldsymbol{\tau}_m(t) & = -\mathbf{B}'_m \dot{\mathbf{x}}_m(t) - \mathbf{f}_{md}(t) & \text{local control} \\
 \boldsymbol{\tau}_s(t) & = -\mathbf{B}'_{s1} \dot{\mathbf{x}}_s(t) + \mathbf{f}_s(t) - \alpha_f \mathbf{f}_{env}(t) & \text{compliance control} \\
 \mathbf{f}_s(t) & = \mathbf{K}'_s \int \Delta \dot{\mathbf{x}}_s(t) dt + \mathbf{B}'_s \Delta \dot{\mathbf{x}}_s(t) & \text{remote control}
 \end{array} \right.$$

and the “traditional” force reflection:

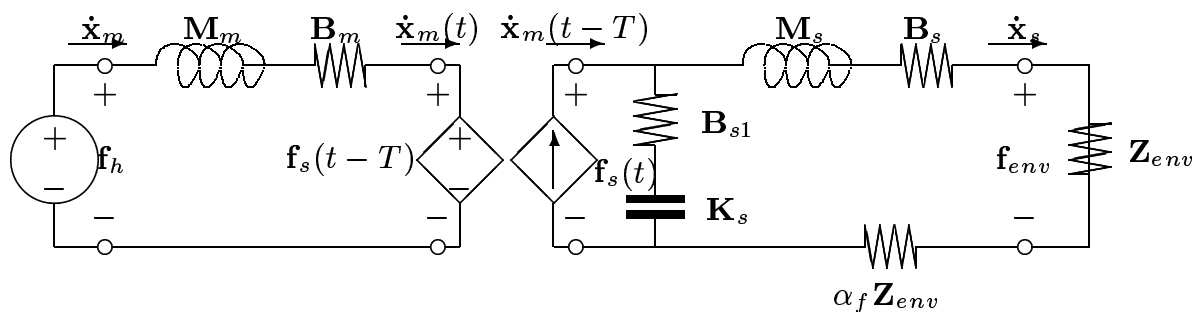
$$\left\{ \begin{array}{ll}
 \mathbf{f}_{md}(t) & = \mathbf{f}_s(t - T) \\
 \dot{\mathbf{x}}_{sd}(t) & = \dot{\mathbf{x}}_m(t - T)
 \end{array} \right.$$

Example of a teleoperation model

With $T = 0$ s, the device is described by the network:

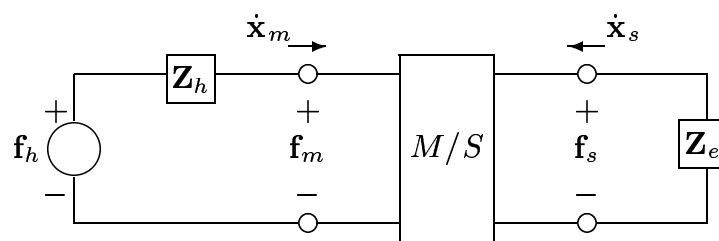


With $T \neq 0$ s, a generator should be included:



Teleoperation system description

Each two-port element and the overall teleoperation system:



can be described in terms of:

$$\begin{aligned}
 (\mathbf{f}_m, \mathbf{f}_s, t) &= \mathbf{Z}(\dot{\mathbf{x}}_m, -\dot{\mathbf{x}}_s, t) && \textit{impedance operator} \\
 (\dot{\mathbf{x}}_m, -\dot{\mathbf{x}}_s, t) &= \mathbf{Y}(\mathbf{f}_m, \mathbf{f}_s, t) && \textit{admittance operator} \\
 (\mathbf{f}_m, -\dot{\mathbf{x}}_s, t) &= \mathbf{H}(\mathbf{f}_s, \dot{\mathbf{x}}_m, t) && \textit{hybrid operator} \\
 (\mathbf{f}_m, \dot{\mathbf{x}}_m, t) &= \mathbf{C}(\mathbf{f}_s, -\dot{\mathbf{x}}_s, t) && \textit{chain operator} \\
 (\mathbf{f} - \dot{\mathbf{x}}, t) &= \mathbf{S}(\mathbf{f} + \dot{\mathbf{x}}, t) && \textit{scattering operator}
 \end{aligned}$$

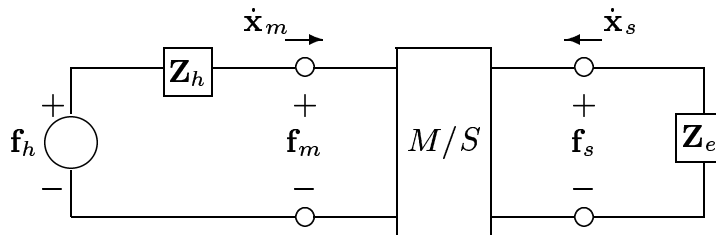
For LTI systems the operators \mathbf{Z} , \mathbf{Y} , \mathbf{H} , \mathbf{C} , \mathbf{S} are transfer matrices.

Teleoperation system description

The most convenient description can be chosen considering:

- distinction between independent and dependent variables,
- generality of the description,
- *stability analysis*,
- *performance evaluation criteria* (hybrid matrix).

Impedance matrix



Considering a LTI two-port element, it is possible to introduce the *impedance matrix* $\mathbf{Z}(s)$ which relates effort (\mathbf{f}) and flow ($\dot{\mathbf{x}}$) variables as:

$$\mathbf{f}(s) = \mathbf{Z}(s) \dot{\mathbf{x}}(s)$$

Considering the master/slave system as a connection of consecutive two-port elements, the impedance matrix of the overall system is given by:

$$\mathbf{f}(s) = \begin{bmatrix} \mathbf{f}_m(s) \\ \mathbf{f}_s(s) \end{bmatrix} = \begin{bmatrix} \mathbf{Z}_{mm}(s) & \mathbf{Z}_{ms}(s) \\ \mathbf{Z}_{sm}(s) & \mathbf{Z}_{ss}(s) \end{bmatrix} \begin{bmatrix} \dot{\mathbf{x}}_m(s) \\ \dot{\mathbf{x}}_s(s) \end{bmatrix} = \mathbf{Z}(s) \dot{\mathbf{x}}(s)$$

Impedance matrix

$$\mathbf{Z}(s) = \begin{bmatrix} \mathbf{Z}_{mm}(s) & \mathbf{Z}_{ms}(s) \\ \mathbf{Z}_{sm}(s) & \mathbf{Z}_{ss}(s) \end{bmatrix}$$

With respect to the block structure of the impedance matrix $\mathbf{Z}(s)$, two particular cases are of interest:

- **Bilateral Teleoperation:** the impedance matrix (the teleoperator) is defined bilateral when both the off-diagonal blocks of $\mathbf{Z}(s)$, \mathbf{Z}_{ms} and \mathbf{Z}_{sm} , are not null:

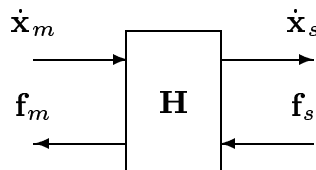
$$\mathbf{Z}_{ms} \neq \mathbf{0} \quad \mathbf{Z}_{sm} \neq \mathbf{0}$$

- **Reciprocal Teleoperation:** the impedance matrix (the teleoperator) is defined reciprocal when the off-diagonal blocks of $\mathbf{Z}(s)$, \mathbf{Z}_{ms} and \mathbf{Z}_{sm} , are equal:

$$\mathbf{Z}_{ms} = \mathbf{Z}_{sm}$$

Hybrid matrix

The impedance description is not general since it cannot describe particular two-port elements, i.e. the ideal transformer. A more general description for teleoperation systems is given by the *hybrid matrix*, defined according to the following sign convention:



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

where:

$$\begin{aligned} h_{11} &= \left. \left[\frac{\partial f_m}{\partial \dot{x}_m} \right] \right|_{f_s=0} & h_{12} &= \left. \left[\frac{\partial f_m}{\partial f_s} \right] \right|_{\dot{x}_m=0} \\ h_{21} &= \left. \left[-\frac{\partial \dot{x}_s}{\partial \dot{x}_m} \right] \right|_{f_s=0} & h_{22} &= \left. \left[-\frac{\partial \dot{x}_s}{\partial f_s} \right] \right|_{\dot{x}_m=0} \end{aligned}$$

Hybrid matrix

Physical meaning of the hybrid matrix elements:

$$\begin{bmatrix} \mathbf{f}_m \\ -\dot{\mathbf{x}}_s \end{bmatrix} = \begin{bmatrix} \mathbf{Z}_{in} & \text{force ratio} \\ \text{velocity ratio} & \mathbf{Z}_{out}^{-1} \end{bmatrix} \begin{bmatrix} \dot{\mathbf{x}}_m \\ \mathbf{f}_s \end{bmatrix}$$

\mathbf{Z}_{in} and \mathbf{Z}_{out} : input and output teleoperator impedances.

IDEAL HYBRID MATRIX. In case of ideal telepresence, forces and velocities of master and slave are equal, and therefore:

$$\begin{cases} \mathbf{f}_s = \mathbf{f}_m \\ \dot{\mathbf{x}}_s = \dot{\mathbf{x}}_m \end{cases} \implies \mathbf{H}_{ideal}(s) = \begin{bmatrix} \mathbf{0}_n & \mathbf{I}_n \\ -\mathbf{I}_n & \mathbf{0}_n \end{bmatrix}$$

Hybrid vs Impedance

Assuming impedances at the master and slave sites described by the matrices, \mathbf{Z}_m and \mathbf{Z}_s :

$$\begin{aligned} \mathbf{f}_s &= \mathbf{Z}_s \dot{\mathbf{x}}_s \\ \mathbf{f}_m &= \mathbf{Z}_m \dot{\mathbf{x}}_m \end{aligned}$$

the impedance transmitted to the operator can be computed as a function of the hybrid matrix.

In the 1 dof case, for example, the following relationship between actual and transmitted impedance is obtained:

$$Z_m(s) = \frac{[h_{11}(h_{22}Z_s + 1) - h_{12}h_{21}Z_s]}{(h_{22}Z_s + 1)}$$

Hybrid vs Impedance

The possibility of exploiting the relation between master and slave impedance matrices consists in:

- introduction of a scaling factor (position and/or force),
- use of environment model for deriving impedances functions to be used within the control loop as real-time simulation of the task (impedance shaping).

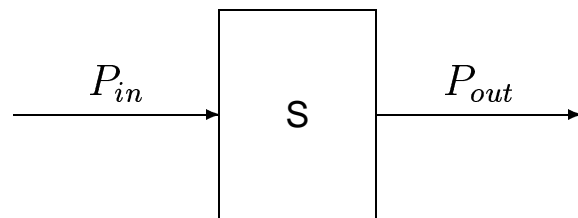
The exploitation of the impedance relationships results in overcoming the transparency design goal and it is essential in several fields, i.e.:

- different position scale devices (macro-micro manipulation),
- simulator devices,
- haptic interfaces.

Wave variables

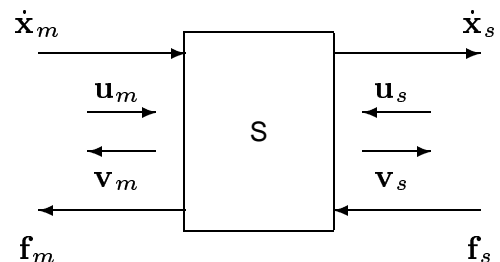
Let consider the total power flow in a two-port element as composed of two terms, the *input power* P_{in} and *output power* P_{out} :

$$\begin{aligned}
 P &= P_{in} - P_{out} = \mathbf{f}^T \dot{\mathbf{x}} \\
 &= [\mathbf{f}_m^T, \mathbf{f}_s^T] \begin{bmatrix} \dot{\mathbf{x}}_m \\ -\dot{\mathbf{x}}_s \end{bmatrix} \\
 &= \frac{1}{2} (\mathbf{u}^T \mathbf{u} - \mathbf{v}^T \mathbf{v})
 \end{aligned}$$



where

$$\begin{aligned}
 \mathbf{u} &= [\mathbf{u}_m^T \ \mathbf{u}_s^T]^T & \mathbf{v} &= [\mathbf{v}_m^T \ \mathbf{v}_s^T]^T \\
 \mathbf{u}_m &= \frac{1}{\sqrt{2}} (\mathbf{f}_m + \dot{\mathbf{x}}_m) & \mathbf{u}_s &= \frac{1}{\sqrt{2}} (\mathbf{f}_s - \dot{\mathbf{x}}_s) \\
 \mathbf{v}_m &= \frac{1}{\sqrt{2}} (\mathbf{f}_m - \dot{\mathbf{x}}_m) & \mathbf{v}_s &= \frac{1}{\sqrt{2}} (\mathbf{f}_s + \dot{\mathbf{x}}_s)
 \end{aligned}$$



Wave variables

With

$\mathbf{u} \rightarrow$ input wave $\mathbf{v} \rightarrow$ output wave

- Wave variables can be applied both to linear and non-linear systems.
- From physical intuition, in stable system the “amplitude” of \mathbf{v} is less than the “amplitude” of \mathbf{u} :

$$\frac{1}{2} \int \mathbf{v}^T \mathbf{v} dt \leq \frac{1}{2} \int \mathbf{u}^T \mathbf{u} dt$$

i.e. the “gain” of the system is less than one.

- In the definition of wave variables, time-delay is not considered: time-delay does not affect the “amplitude” of the wave.
- Different I/O properties may be achieved introducing passive elements.

Scattering matrix

The Scattering operator (or matrix) relates the input/output *wave variables*, \mathbf{u} and \mathbf{v} , at each port of the teleoperator instead of the power variables, $\dot{\mathbf{x}}$ and \mathbf{f} .

Definition. Given an n -port system, the *scattering matrix* (or *scattering operator*) is defined as the operator which relates input and output wave variables as:

$$\mathbf{v}(t) = \mathbf{S}(t)\mathbf{u}(t) \quad \Longleftrightarrow \quad \mathbf{f}(t) - \dot{\mathbf{x}}(t) = \mathbf{S}(t) [\mathbf{f}(t) + \dot{\mathbf{x}}(t)]$$

for LTI system:

$$\mathbf{v}(s) = \mathbf{S}(s)\mathbf{u}(s) \quad \Longleftrightarrow \quad \mathbf{f}(s) - \dot{\mathbf{x}}(s) = \mathbf{S}(s) [\mathbf{f}(s) + \dot{\mathbf{x}}(s)]$$

Scattering and hybrid representation are related by the equation:

$$\mathbf{S}(s) = \begin{bmatrix} \mathbf{I}_n & \mathbf{0}_n \\ \mathbf{0}_n & -\mathbf{I}_n \end{bmatrix} [\mathbf{H}(s) - \mathbf{I}_{2n}] [\mathbf{H}(s) + \mathbf{I}_{2n}]^{-1}$$

Scattering vs Passivity

Theorem. An LTI n -port element with scattering matrix $\mathbf{S}(s)$ is passive if and only if

$$\|\mathbf{S}(s)\| \leq 1$$

Corollary. An LTI n -port element described by the scattering matrix $\mathbf{S}(s)$ is passive if and only if

$$\|\mathbf{S}(s)\| = \sup_{\omega} \lambda_{max}^{1/2} \{ \mathbf{S}^*(j\omega) \mathbf{S}(j\omega) \} \leq 1$$

where $\lambda_{max} \{ \mathbf{S}(j\omega) \}$ is the maximum eigenvalue and $\mathbf{S}^*(j\omega)$ the transpose conjugate of $\mathbf{S}(j\omega)$.

Scattering vs Passivity

Considerations.

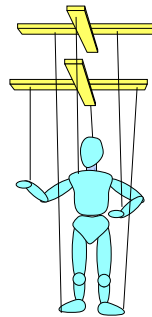
- Connection of passive n -port preserves passivity.
- In traditional force reflection teleoperation systems time-delay instabilities are originated by the non-passive features of the communication line (local controllers assuming to stabilize the respective subsystems).
- The use of a particular communication channel based on the analogous of a lossless transmission line results in a passive communication channel (Passivity Based Teleoperation).

Robotic Telemanipulation: Control Aspects

Claudio Melchiorri

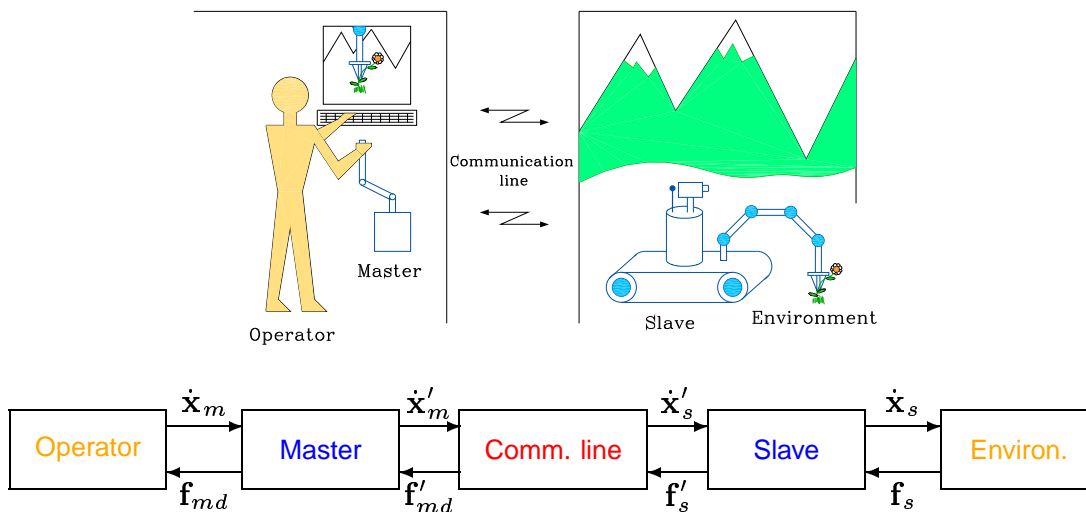


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Control strategies for telemanipulation systems



There are particular features unique to telemanipulation systems:

- Unstructured environment;
- Presence of a human operator for high-level control:
 - man/machine interface;
 - training of specialized personnel;

Control strategies for telemanipulation systems

- In general, two distinct and different robotic systems (master & slave):
 - different kinematics;
 - different work space;
 - different impedance characteristics;
 - different dynamics properties;
- Transmission of signals to remote sites (master \Leftrightarrow slave):
 - choice of suitable signals (position, force, vision, temperature, ...);
 - choice and computation of the “coordination” signal;
- Time delays (limited bandwidth and/or remote location):
 - instability problems if signals are fed back to master site.

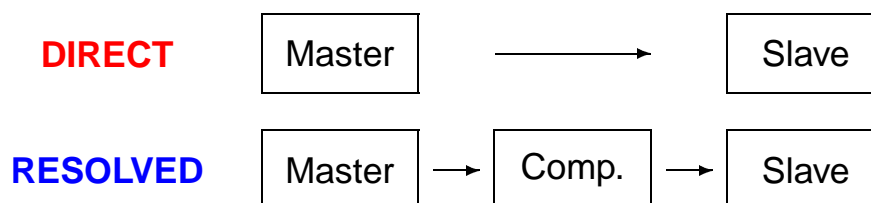
About the control:

- “local” (master & slave) controllers are assumed;
- the attention is focused mainly in the overall control loop:
operator \Leftrightarrow master \Leftrightarrow communication \Leftrightarrow slave \Leftrightarrow environment
- in particular, the transmission modalities of the relevant signals (velocities/forces/...) are of primary importance.

Control strategies for telemanipulation systems

Several control schemes for telemanipulators have been developed. Among the most known, one can mention:

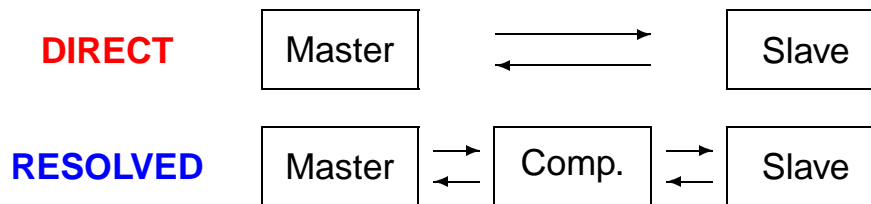
- Unilateral rate control:
 - direct
 - resolved
- Unilateral position control:
 - direct
 - resolved



Control strategies for telemanipulation systems

• Bilateral position control:

- direct
- resolved

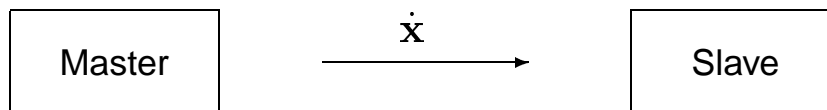


• Operator aiding control:

- filtering
- scaling
- referencing
- motion constraints or compensation
- simulation

Unilateral rate control

Direct rate control:



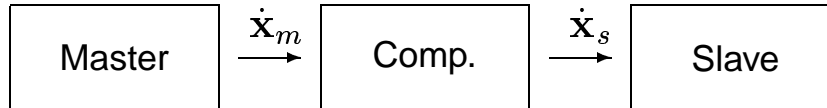
- The controller output is relayed directly to the slave servos, where it is interpreted as a VELOCITY command.
- Usually, there is a one-to-one correspondence between master's and slave's dof.
- Commanded velocities can be either preset or continuously variable.

Some considerations:

- + Simple implementation;
- + Small master motion can cover large workspaces accurately;
- + Accuracy does not depend on joint resolution;
- Operator experiments coordination difficulties;
- Not compatible in general with force feedback;
- Necessity of visual information on slave location (or mental integration).

Unilateral rate control

Resolved rate control:



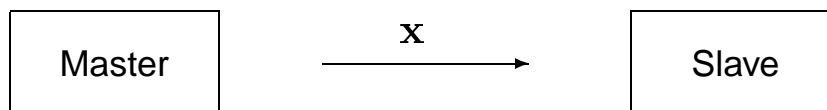
- The controller output is interpreted as a VELOCITY command by the slave servos, after being properly elaborated by the control system (typically: change of reference frame).
- Usually, there is an one-to-one correspondence between master's and slave's dof.
- Commanded velocities can be either preset or continuously variable.

Some considerations:

- + Allows change of reference frames;
- + Different control gains;
- + Small master motion can cover large workspaces accurately;
- + Accuracy does not depend on joint resolution;
- + Much simpler use for the operator;
- Moderate/high computational burden;
- Not compatible in general with force feedback;
- Necessity of visual information on slave location (or mental integration).

Unilateral position control

Direct unilateral position control:



- The controller output is relayed directly to the slave servos, and is interpreted as a DESIRED JOINT MOTION command.
- Usually, there is an one-to-one correspondence between master's and slave's dof.

Some considerations:

- + Simple implementation;
- + Control input corresponds to desired slave's servos position;
- High resolution position sensors on both master and slave;
- Spatial correspondence depends on master and slave configuration;
- No force feedback: the operator input can exceed the maximum slave velocity;
- Control frame of the end-effector cannot be specified;
- Limited use of scaling.

Unilateral position control

Resolved unilateral position control:



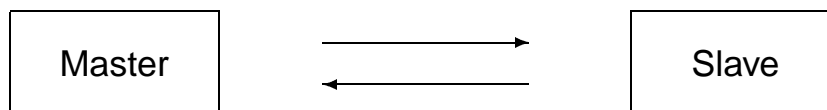
- The controller output is interpreted as a DESIRED JOINT MOTION command by the slave servos, expressed in a convenient reference frame attached to the slave (end-effector, ...).
- Elaborations performed by the control systems.
- Usually, there is an one-to-one correspondence between master's and slave's dof.

Some considerations:

- + Choice of reference frame;
- + Spatial correspondence does not depend on master and slave configuration;
- + Scaling can be easily incorporated;
- High resolution position sensors on both master and slave;
- No force feedback: the operator input can exceed the maximum slave velocity;
- Since the configuration of master and slave may differ, configuration feedback may not be available.

Bilateral position control

Direct bilateral position control:



- The controller output is relayed directly to the slave servos, and is interpreted as a DESIRED JOINT MOTION command.
- Simultaneously, the slave position is sent back to the master controller, where it is interpreted as a REQUIRED JOINT POSITION.
- The result is the generation of a force at both the master and slave site when their positions are different.

Some considerations:

- + Simple implementation;
- + Force feedback;
- + Control input corresponds to desired slave's servos position;
- High resolution position sensors on both master and slave;
- Increased controller complexity (wrt unilateral position control);
- Spatial correspondence depends on master and slave configuration;
- Control frame of the end-effector cannot be specified;

Bilateral position control

Resolved bilateral position control:



- Master joint signals are transformed into equivalent Cartesian movements of the slave reference point, and then transformed in servo joint commands;
- Similarly, the slave position is transformed and sent back to the master controller.
- When the positions of master and slave are different, there is force reflection at the master and force generation at the slave site.

Some considerations:

- + Choice of reference frame;
- + Spatial correspondence can be obtained regardless of controller design;
- + Motion and force scaling easily achievable;
- Relevant computational burden;
- Since the configuration of master and slave may differ, configuration feedback may not be available;
- High resolution position sensors on both master and slave.

Operator aiding control

FILTERING: process in which extraneous motions superimposed to the control signal (by the operator) are detected and eliminated.
Smoothness of inputs; possible phase errors.

SCALING: a “geometric gain” may be used between master and slave motions. Useful for gross motions and/or precision operations.

RE-REFERENCING (or INDEXING): possibility of having the slave workspace always mapped in a proper location of master workspace.

CONTROL COORDINATES RE-REFERENCING: possibility of changing the reference frame in which the motions are expressed (tool, base, and so on).

MOTION CONSTRAINTS: constraints are artificially added to the slave site in order to protect or improve the control action.

COMPENSATION TECHNIQUES: data to/from the slave are artificially modified in order to enhance or compensate some (physical) effects, such as dynamics, friction, tracking of moving objects, and so on.

Bilateral control

Usually, the goals of a telemanipulator are to operate in an unstructured environment, and therefore the human control is required.

Since the operator represents the main “controller” of the system, he/she requires to be informed about the evolution of the task and about some pertinent information:

- presence of data feedback from the slave to the master;
- development of a proper user interface.

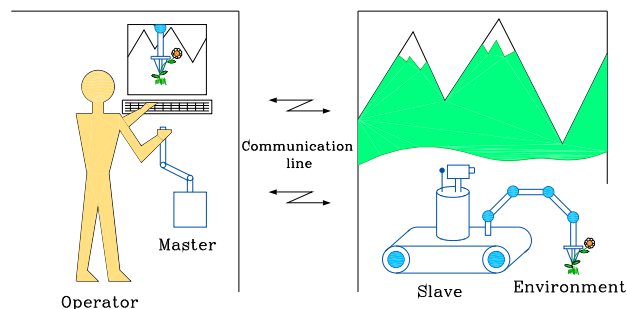
Signals fed back to the master may be related to:

- forces applied to the environment;
- relevant positions of the slave;
- graphical video data;
- tactile or acoustic information;
- ...

The choice of the type of signals transmitted to the operator has strong implications on the control properties and performances of the system.

Bilateral control

COORDINATION SIGNAL(s): The signal(s) transmitted back to the operator.



The term ‘coordination’ is used to indicate a signal computed as a function of the master and slave variables, in order to obtain their reciprocal tracking.

Usually:

- The operator specifies a desired velocity ($\dot{\mathbf{x}}_m$) to the environment through the master, the communication channel and the slave,
- The operator receives back a force signal (\mathbf{f}_{md}).

Bilaterally controlled teleoperator: when the flow of the signals can be reversed, i.e. the operator may assign a force and receives back a velocity information.

This is equivalent to reversing the roles of the master and the slave.

Possible control design goals

In designing the overall control systems, some goals can be considered:

- Telepresence;
- Telefunctioning:
 - Power scaling;
 - Impedance scaling;
- Impedance shaping.

Possible control design goals

Telepresence

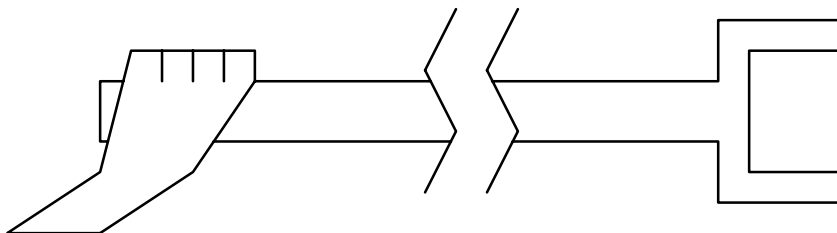
Main goal of the control system is to have, in steady state, the slave velocity equal to the master velocity, i.e.

$$\dot{\mathbf{x}}_s = \dot{\mathbf{x}}_m$$

and similarly for the forces

$$\mathbf{f}_{md} = \mathbf{f}_s$$

In this case, the teleoperator is defined *transparent*.

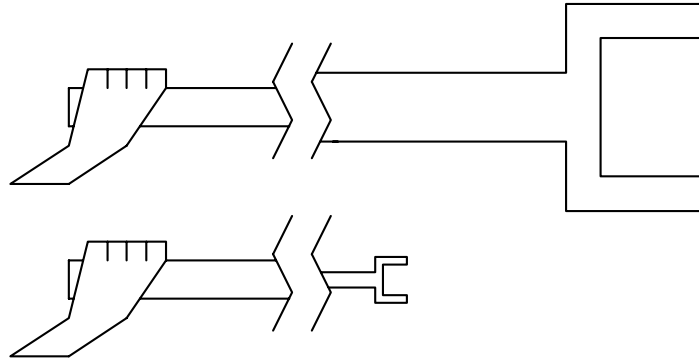


Possible control design goals

Telefunctioning

This is a more general approach than telepresence. In this case, requirements for the control system are

$$\begin{aligned}\dot{\mathbf{x}}_s &= \lambda_v \dot{\mathbf{x}}_m \\ \mathbf{f}_m &= \lambda_f \mathbf{f}_s\end{aligned}$$



Possible control design goals

Examples of telefunctioning:

- teleoperation systems in which the operator experiences scaled-down values of the forces at the slave side,
- teleoperation system with scaled-down position (velocities) as in microsurgery applications,
- the human operator while maneuvering a rigid body should feel forces as he was maneuvering a light single-point mass.

In these examples, one relationship between master/slave variables is specified. More in general, three independent relationships can be assigned between the four variables:

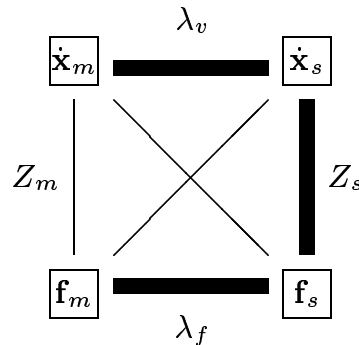
$$\begin{cases} \dot{\mathbf{x}}_s = \lambda_v \dot{\mathbf{x}}_m \\ \mathbf{f}_m = \lambda_f \mathbf{f}_s \\ \mathbf{f}_s = Z_s \dot{\mathbf{x}}_s \end{cases} \quad \text{impedance } Z = (M_s + b) = \frac{\mathbf{f}}{\dot{\mathbf{x}}}$$

Possible control design goals

A possible set of relationships between velocities $\dot{\mathbf{x}}_m$, $\dot{\mathbf{x}}_s$ and forces \mathbf{f}_m , \mathbf{f}_s is:

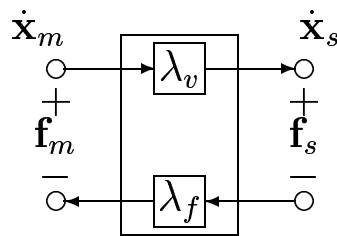
$$\begin{aligned}\dot{\mathbf{x}}_s &= \lambda_v \dot{\mathbf{x}}_m \\ \mathbf{f}_m &= \lambda_f \mathbf{f}_s \\ \mathbf{f}_s &= Z_s \dot{\mathbf{x}}_s\end{aligned}$$

In general, there are four relations between velocities/forces, but only three can be independently assigned.



- Telepresence can be considered a subclass of telefunctioning: $\lambda_v = \lambda_f = 1$.
- Telepresence realizes a dynamic similarity between master/slave variables.

Power and impedance scaling devices



At the moment, there is a noticeable attention for master/slave teleoperation systems under different conditions of:

dimensions,

forces,

power.

In particular, two possible classes of these devices are:

- *strength-increasing devices*: human power amplification,
- *dexterity-increasing devices*: increasing of the dexterity performances (Macro-Micro Bilateral Manipulators, MMBM).

Power and impedance scaling devices

The ability of the operator in manipulating the object is increased in terms of power or dexterity.

Within the class of Power Scaling Devices:

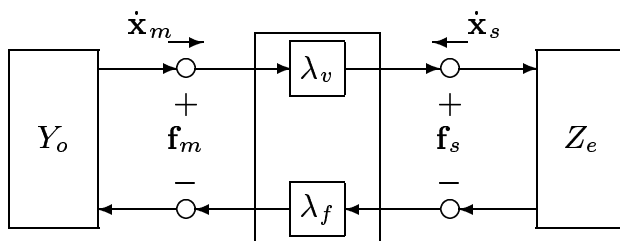
- “MAN-AMPLIFIERS” ('60): coordination of several devices in order to obtain the required power level,
- “ACTIVE PROSTHESIS” ('60): greater extent of power respect to prosthesis muscle activated,
- “EXTENDERS” and “EXTENDED PHYSIOLOGICAL PROPRIOCEPTION” (EPP) ('80): excessive fatigue experienced by the operator while operating man-amplifiers and active prosthesis.

Power and impedance scaling devices

These devices result in particular generalized power amplifiers:

- operational amplifiers are information flow processors and result in unilateral elaboration (ideal input/output impedances),
- power scaling devices are power flow processing elements and result in bilateral elaboration (power couplings between the elements, non-ideal input/output impedances).

Ideal power scaling device:



- λ_v velocity scaling factor,
- λ_f force scaling factor,
- Y_o operator admittance function,
- Z_e environment impedance function
 $[Z = (Ms + b) = \frac{f}{x}]$.

From

$$\dot{x}_m = \frac{1}{\lambda_v} \dot{x}_s \quad f_m = \lambda_f f_s$$

the power contributions at the two ports of the device are related by:

$$\dot{x}_m f_m = \frac{\lambda_f}{\lambda_v} \dot{x}_s f_s$$

The coefficient λ_f/λ_v is the *power factor* of the telemanipulation system.

Power and impedance scaling devices

Moreover, the apparent impedance transmitted to the operator results:

$$Z_{app} = \frac{\mathbf{f}_m}{\dot{\mathbf{x}}_m} = \frac{\lambda_f \mathbf{f}_s}{\dot{\mathbf{x}}_s / \lambda_v} = \lambda_v \lambda_f \frac{\mathbf{f}_s}{\dot{\mathbf{x}}_s} = \lambda_v \lambda_f Z_e$$

The **impedance factor** of the bilateral system is given by $\lambda_v \lambda_f$.

Two relations with two scaling factors:

$$\begin{aligned} \dot{\mathbf{x}}_m \mathbf{f}_m &= \frac{\lambda_f}{\lambda_v} \dot{\mathbf{x}}_s \mathbf{f}_s \\ Z_{app} &= \lambda_v \lambda_f Z_e \end{aligned}$$

By defining a proper selection of the velocity/force scaling factors, it is possible to independently obtain certain values of the power and impedance factors:

- scaling the power;
- scaling the impedance.

Force scale factor

In order to have a unitary impedance factor, given a position/velocity factor λ_v , λ_f should be the inverse of the position scale factor:

$$\lambda_f = \frac{1}{\lambda_v}$$

Therefore, the apparent impedance Z_{app} transmitted to the operator equals the impedance Z_s :

$$Z_{app} = \lambda_v \lambda_f Z_s = Z_s$$

Nevertheless, it is possible (and sometimes desirable) to adjust the transmitted impedance by varying λ_v and λ_f :

- $\lambda_v > \frac{1}{\lambda_f}$: the apparent impedance is *magnified*;
- $\lambda_v = \frac{1}{\lambda_f}$: the apparent impedance is *unscaled*;
- $\lambda_v < \frac{1}{\lambda_f}$: the apparent impedance is *scaled down*.

Force scale factor

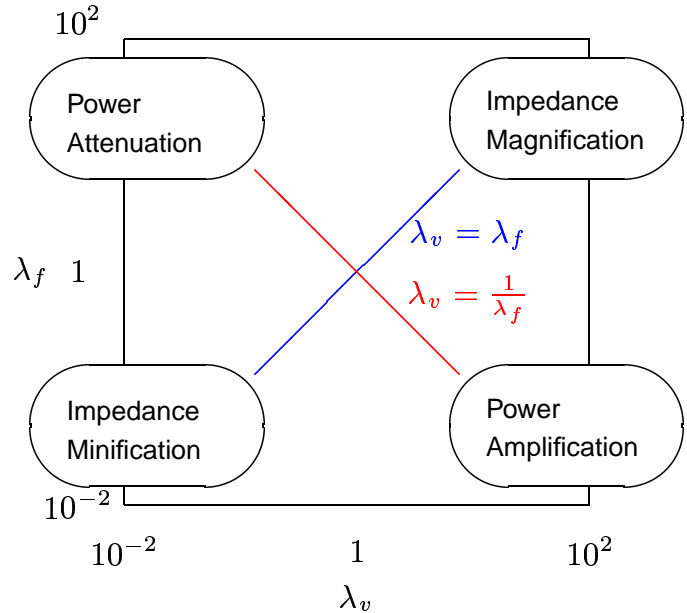
Similarly, since the power gain of the teleoperation device is:

$$\frac{P_s}{P_m} = \frac{\lambda_v}{\lambda_f}$$

then $\lambda_f = \lambda_v$ defines the locus of unity power gain (passivity).

Moreover:

- $\lambda_f > \lambda_v$:
power is attenuated from the operator to the task;
- $\lambda_f = \lambda_v$:
power is the same at both sides;
- $\lambda_f < \lambda_v$:
power is amplified from the operator to the task.



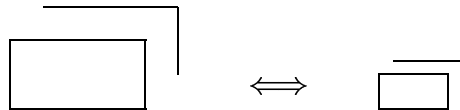
Impedance shaping telemanipulation

Impedance Shaping Telemanipulation:

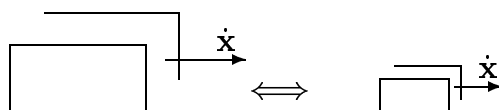
- alternative approach to the transparency methodology,
- evolution of the power and impedance scaling methodology,
- a priori knowledge of an environment model,
- a real-time simulation of a “virtual environment” is used (with the model of the environment) for obtaining the apparent impedance.

In general, it is possible to obtain geometric, kinematic and dynamic similarities:

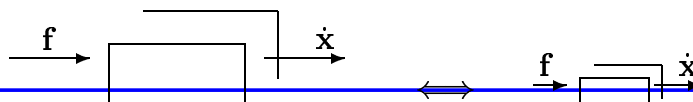
- Geometric similarity: the ratios between all geometric dimensions of master/slave subsystems are equal.



- Kinematic similarity: equality of all geometric dimension ratios and time scaling.



- Dynamic similarity: equality of all geometric dimensional ratios, time scaling and force ratios.



An example

Consider a bilateral macro/micro teleoperator with position scaling factor

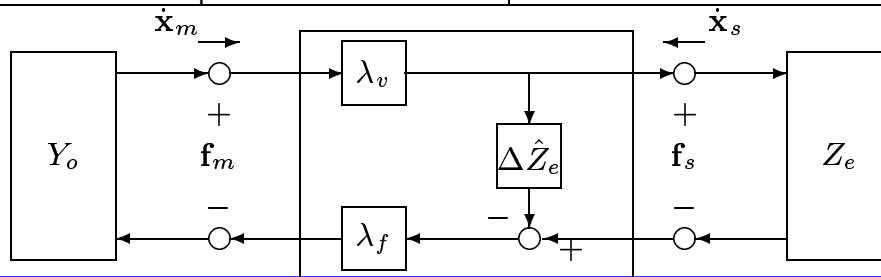
$$\lambda_v = \frac{1}{\alpha}$$

The environment is a mechanical system of mass M_e and viscous friction B_e .

Two possibilities for the choice of the force scaling factor:

- $\lambda_f = \alpha^4$ originates an impedance factor $\lambda_v \lambda_f = \alpha^3$
the apparent impedance is a mass component,
- $\lambda_f = \alpha^3$ originates an impedance factor $\lambda_v \lambda_f = \alpha^2$
the apparent impedance is a viscous friction.

Environment model	$\hat{Z}_e(s) = \hat{M}_e s + \hat{B}_e$
Kinematic similar impedance	$\hat{Z}_e^{ks}(s) = \alpha^3 \hat{M}_e s + \alpha^2 \hat{B}_e$
Virtual environment	$\Delta \hat{Z}_e(s) = (\alpha - 1) \hat{M}_e s$
Apparent impedance transmitted to the operator	$Z_{app}(s) = \alpha^2 ((\alpha - 1) \hat{M}_e s + Z_e(s))$



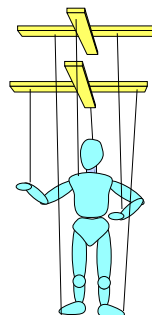
Robotic Telemanipulation:

Control Schemes

Claudio Melchiorri



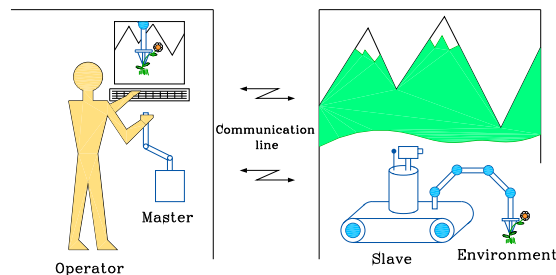
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Some control schemes

Some general considerations:

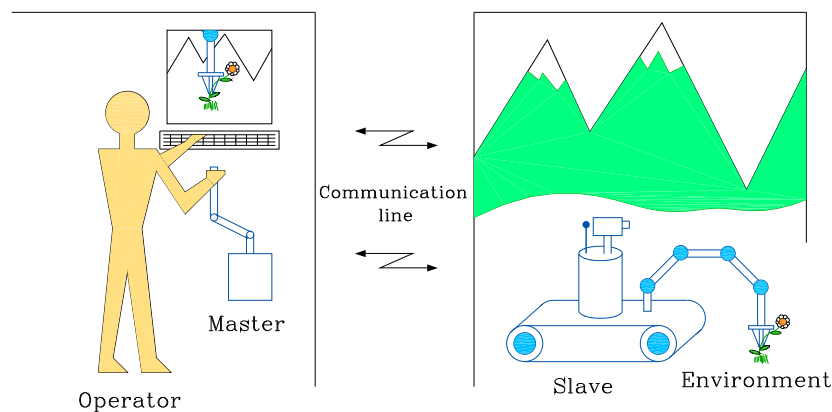
1. in telemanipulation, a relevant control problem is given by the time-delay introduced by the communication channel (more than robots control or slave/environment interaction features);
2. presence of time-delay has to be considered for the stability problems;
3. force feedback to the operator and local compliance control at the slave site have to be designed for avoiding excessive contact forces;
4. telemanipulation systems where only position information are transmitted between master and slave result in very stiff devices with poor performances;
5. in reliable teleoperation a coordination signal (force reflection) is required;
6. direct reflection of the force signal can result in unstable systems.



Some control schemes

Some well known bilateral teleoperation systems:

1. "Traditional" force reflection teleoperation (TFR);
2. "Shared Compliance Control" teleoperation (SCC);
3. Passivity-Based teleoperation;
4. Predictive control.

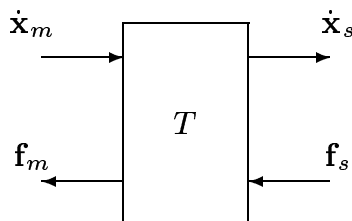


Some control schemes

These control schemes are investigated considering:

1. **Presence of time-delays.** The control schemes will be described and their features in the presence of time-delays discussed.
2. **Scattering theory.** The scattering analysis will be adopted in order to investigate the passivity properties of the control methodologies (hybrid and scattering matrices).
3. **Communication line.** The control schemes are mainly based on different methodologies for the computation of the coordination signal, without dealing with the local controllers.
The analysis considers the communication line properties as a key factor for a suitable definition of the coordination in presence of time-delays.
4. **Limitations.** In the following analysis, the human operator and the environment model are not considered.
5. **Experimental activity.** A simple 1 dof teleoperation device (two one-dof “robots” position and force sensorized) is used for implementing the different control methodologies.

Traditional force reflection



Consider the master/slave systems connected by the simple communication “law”:

$$\begin{cases} \mathbf{f}_{md}(t) &= \mathbf{f}_s(t - T) \\ \dot{\mathbf{x}}_{sd}(t) &= \dot{\mathbf{x}}_m(t - T) \end{cases}$$

where T is the time-delay due to the communication network.

Considerations:

- even in presence of small time-delay (limited bandwidth) instabilities appear;
- the insertion of a force reflection gain $G_{fr} < 1$, i.e.

$$\mathbf{f}_{md}(t) = G_{fr} \mathbf{f}_s(t - T) \quad G_{fr} < 1$$

reduces the performances without producing a valuable improvement of the stability properties;

- the communication channel does not result passive, and this originates instability;
- the non-passive communication channel introduces power contributions in the overall system. These contributions have to be compensated by introducing attenuation in the local controllers.

Modelling the TFR

Given:

1. the master dynamics and communication variables (local master controller):

$$\begin{cases} \mathbf{M}_m \dot{\mathbf{x}}_m(t) &= -\mathbf{f}_{md}(t) - \mathbf{B}_m \dot{\mathbf{x}}_m(t) - \mathbf{K}_h \mathbf{x}_m(t) \\ \mathbf{f}_{md}(t) &= \mathbf{f}_s(t - T) \end{cases}$$

2. the slave dynamics, communication variables and slave local controller:

$$\begin{cases} \mathbf{M}_s \dot{\mathbf{x}}_s(t) &= \mathbf{f}_s(t) - \mathbf{B}_s \dot{\mathbf{x}}_s(t) \\ \dot{\mathbf{x}}_{sd}(t) &= \dot{\mathbf{x}}_m(t - T) \\ \mathbf{f}_s(t) &= \mathbf{K}_p [\mathbf{x}_{sd}(t) - \mathbf{x}_s(t)] \end{cases}$$

where:

- $\mathbf{M}_i, \mathbf{B}_i$ master/slave masses and damping factors,
- \mathbf{K}_h human operator model (stiffness),
- \mathbf{K}_p slave position controller.

Modelling the TFR

From

$$\begin{bmatrix} \mathbf{f}_m \\ -\dot{\mathbf{x}}_s \end{bmatrix} = \mathbf{H} \begin{bmatrix} \dot{\mathbf{x}}_m \\ \mathbf{f}_s \end{bmatrix}$$

the following hybrid matrix is obtained:

$$\mathbf{H}(s) = \begin{bmatrix} 0 & e^{-sT} \\ -e^{-sT} & 0 \end{bmatrix}$$

By using the hybrid/scattering relationship, the scattering matrix $\mathbf{S}(s)$, computed for $s = j\omega$, is

$$\mathbf{S}(j\omega) = \begin{bmatrix} -j \tan(\omega T) & \sec(\omega T) \\ \sec(\omega T) & j \tan(\omega T) \end{bmatrix}$$

Modelling the TFR

The norm of the scattering matrix for TFR is:

$$\|\mathbf{S}(j\omega)\| = \sup_{\omega} \{ |\tan(\omega T)| + |\sec(\omega T)| \}$$

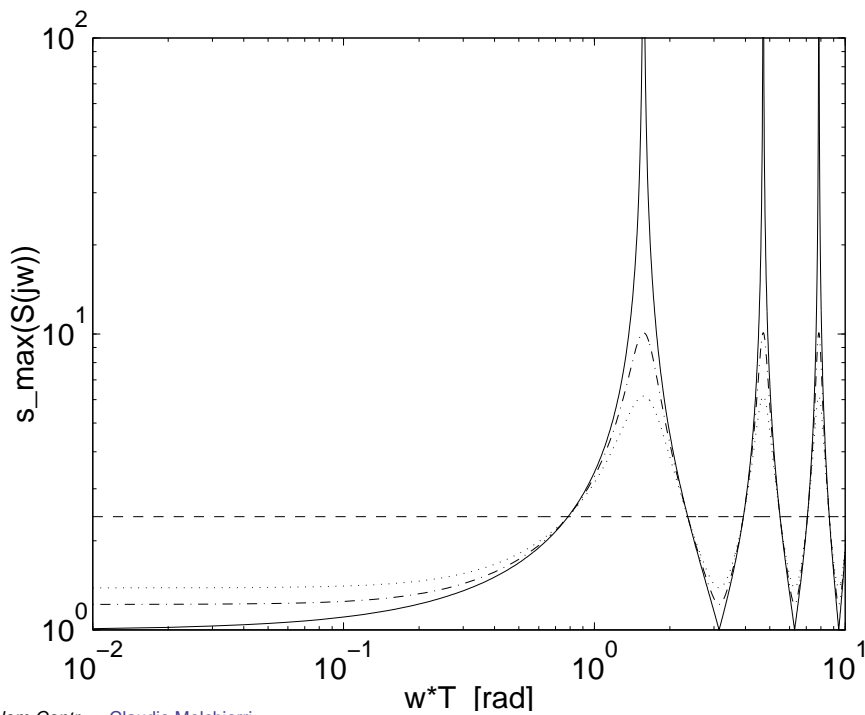
The norm of the scattering matrix results infinite and the passivity conditions are not verified even for very low time-delays T .

In practical applications, stability can be achieved only by inserting attenuation at the local controllers in order to compensate the power components introduced by the communication channel.

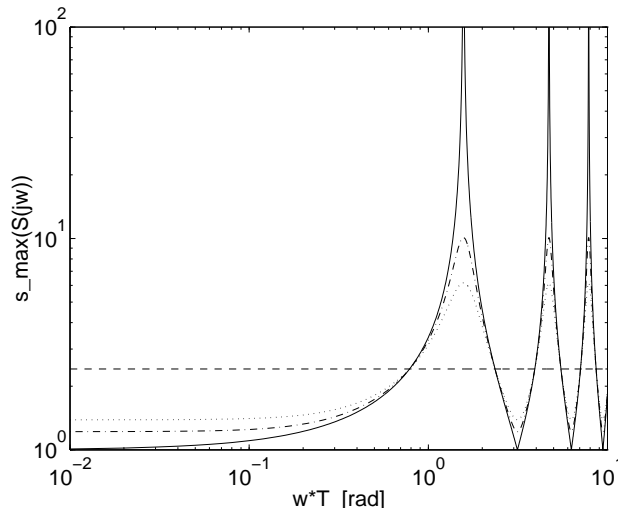
TFR: scattering analysis

The maximum singular value of the scattering matrix, $\sigma_{max} \{ \mathbf{S}(j\omega) \}$, of TFR teleoperators is reported in the figure:

- as a function of ωT ,
- for different values of the force reflection gain G_{fr} .



- $G_{fr} = 0.0$ (dashed),
- $G_{fr} = 0.5$ (dotted),
- $G_{fr} = 1.0$ (solid),
- $G_{fr} = 1.5$ (dashdot).

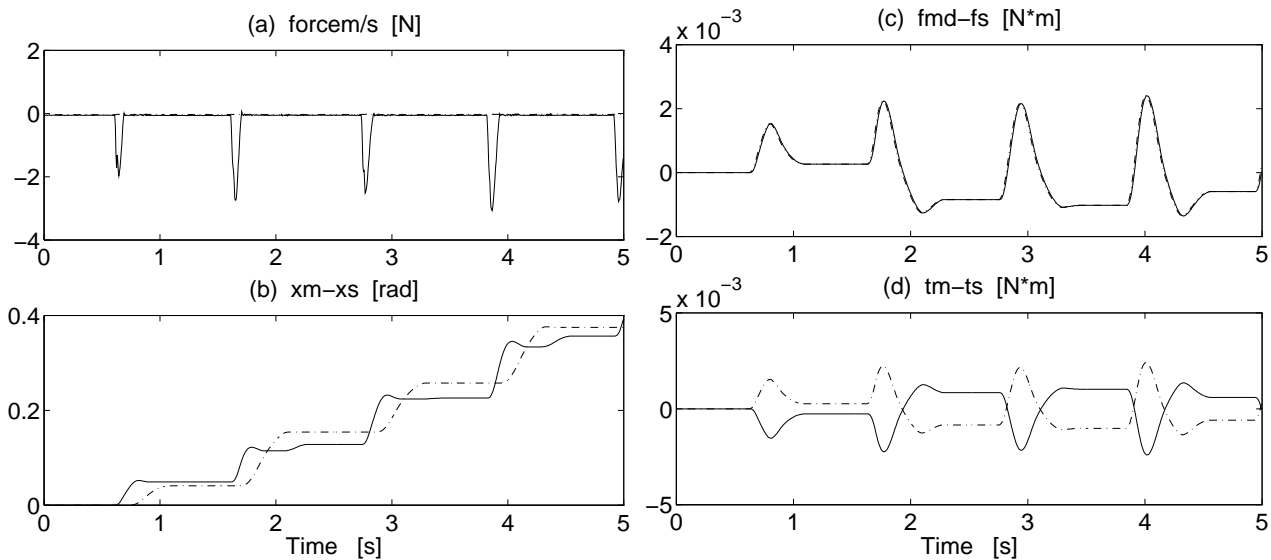


- $\|S(j\omega)\| \geq 1, \forall G_{fr} \geq 0.0$, i.e. the system is not passive $\forall G_{fr}$.
- The norm of the scattering matrix is unbounded for $G_{fr} = 1.0$, bounded for $G_{fr} \neq 1.0$.
- The non-passivity features of the TFR do not change by reducing the force reflection gain.

TFR Verification

- Repetitive operator actions (force impulses) on the master,
- without interaction at the slave site,
- time-delays programmed to:

$$T = 0.01 \text{ s}$$



(a) operator/environment forces

(b) master/slave positions

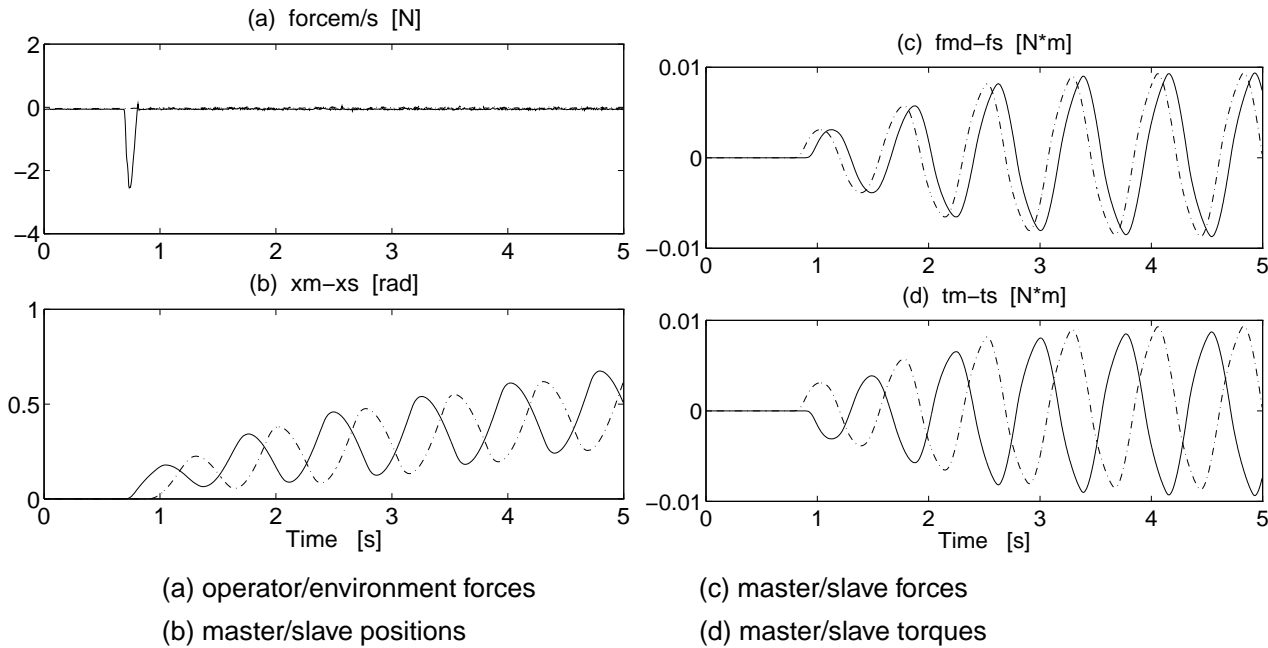
(c) master/slave forces

(d) master/slave torques

TFR Verification

- Repetitive operator actions (force impulses) on the master,
- without interaction at the slave site,
- time-delays programmed to:

$$T = 0.1 \text{ s}$$



Shared Compliance Control (SCC)

Shared Compliance Control deals with:

- interaction of the slave with the environment;
- the time-delay problems.

Two basic features:

- the particular coordination signal;
- sharing the teleoperated capability with some degree of slave autonomy.

Coordination signal: based on the *Position-Error Based Force Reflection*

$$\mathbf{f}_{md}(t) = G_{fr} [\mathbf{x}_m(t) - \mathbf{x}_s(t - T)]$$

It is proportional to the error of the actual master posture and the delayed slave one, through the force reflection gain G_{fr} .

Shared Compliance Control (SCC)

$$\mathbf{f}_{md}(t) = G_{fr} [\mathbf{x}_m(t) - \mathbf{x}_s(t - T)]$$

The force reflection can be originated by:

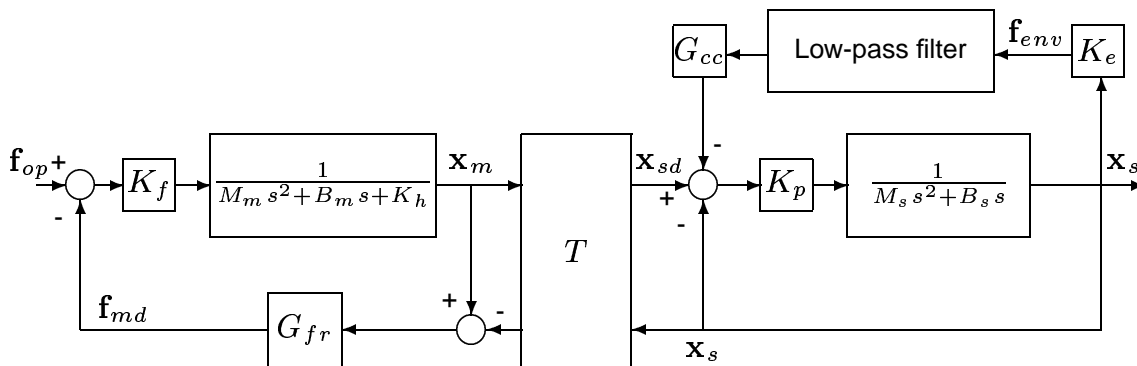
1. interaction at the slave site,
2. time-delays.

Note that the coordination strategy introduces a *compliance* between the robot positions.

Shared control: an autonomous compliance controller is realized at the slave site. Shared compliance is a key-factor for overcoming instabilities due to time-delays.

Shared Compliance Control (SCC)

Overall control scheme:



master dynamics	$1/(M_m s^2 + B_m s + K_h)$
slave dynamics	$1/(M_s s^2 + B_s s)$
force reflection gain	G_{fr}
shared compliance controller	G_{cc}
environment model	K_e

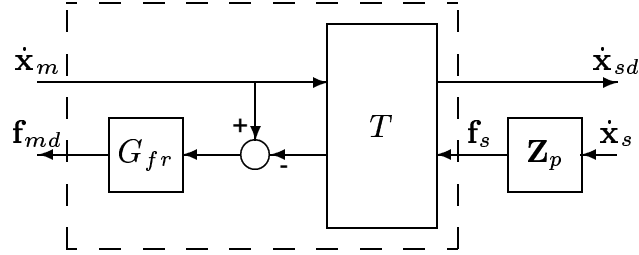
- Force measurements are used at the slave site (compliance controller).
- Position errors for deriving the coordination signal.

SCC: Stability Analysis

The time-domain description of the network is:

$$\begin{cases} \dot{\mathbf{x}}_{md}(t) = G_{fr} [\mathbf{x}_m(t) - \mathbf{x}_s(t - T)] \\ \mathbf{x}_{sd}(t) = \mathbf{x}_m(t - T) \end{cases}$$

In order to apply the network theory and compute the hybrid matrix, we consider the following scheme:



The impedance \mathbf{Z}_p is introduced in order to represent the slave variables as power factors $\dot{\mathbf{x}}_{sd}$ and \mathbf{f}_s , thus allowing the hybrid representation.

SCC: Stability Analysis

If an unitary value for \mathbf{Z}_p is considered, the system is described by:

$$\mathbf{H}(s) = \begin{bmatrix} \frac{G_{fr}}{s} & -G_{fr}e^{-sT} \\ -e^{-sT} & 0 \end{bmatrix}$$

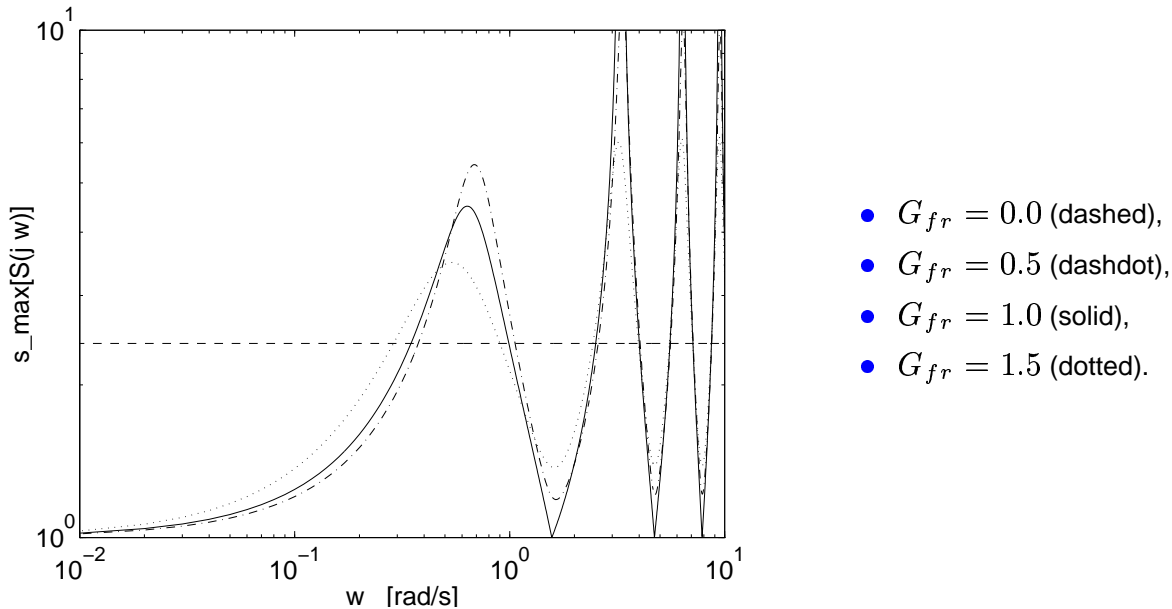
and the scattering matrix is:

$$\mathbf{S}(j\omega) = \begin{bmatrix} \frac{j\omega - G_{fr} + G_{fr}e^{-2j\omega T} j\omega}{-j\omega - G_{fr} + G_{fr}e^{-2j\omega T} j\omega} & \frac{-2G_{fr}e^{-j\omega T} j\omega}{-j\omega - G_{fr} + G_{fr}e^{-2j\omega T} j\omega} \\ \frac{-2e^{-j\omega T} j\omega}{-j\omega - G_{fr} + G_{fr}e^{-2j\omega T} j\omega} & \frac{j\omega + G_{fr} + G_{fr}e^{-2j\omega T} j\omega}{-j\omega - G_{fr} + G_{fr}e^{-2j\omega T} j\omega} \end{bmatrix}$$

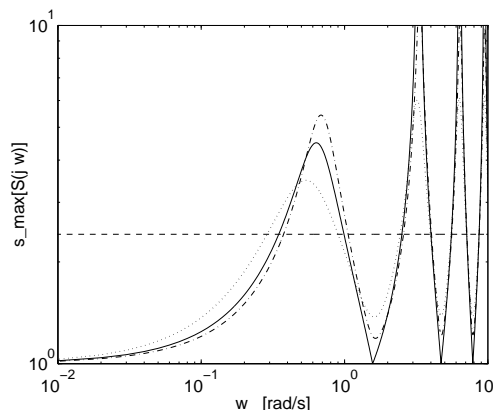
SCC: Stability Analysis

The maximum singular value, $\sigma_{max} \{ \mathbf{S}(j\omega) \}$, of the scattering matrix of SCC is reported in the figure:

- for different G_{fr} values,
- for $T = 1$ s.



SCC: Stability Analysis



- SCC is not passive for any value of G_{fr} and for any T ;
- Even if at low frequency $\sigma_{max} \{ \mathbf{S}(j\omega) \} \simeq 1.0$, local controllers have to be considered for attenuation of energy contributions of the communication network.

In any case, stability may be achieved depending on:

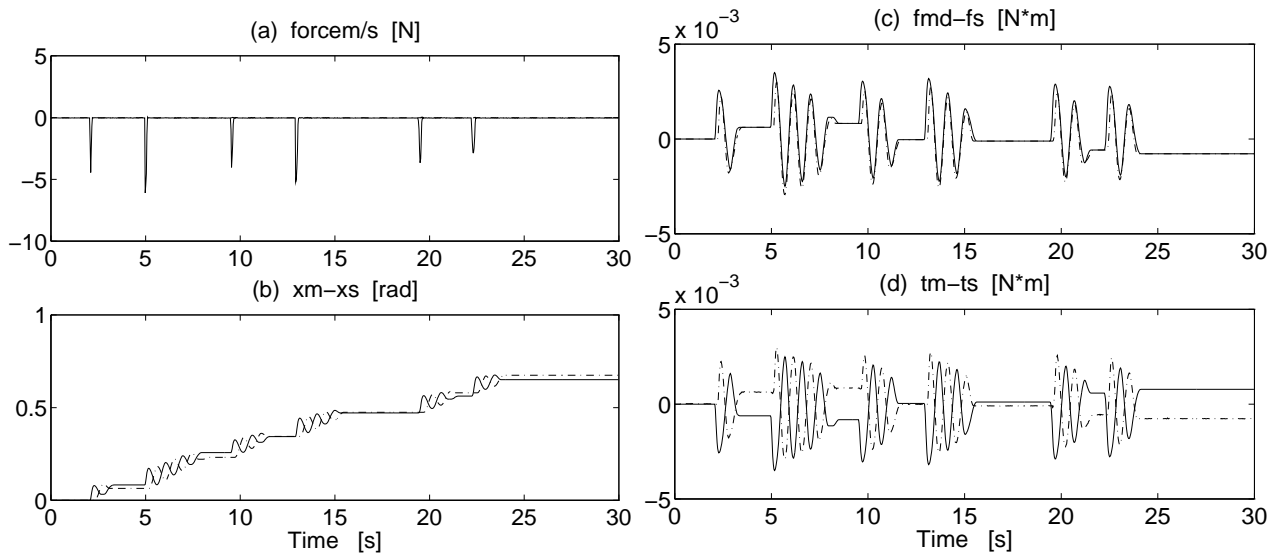
- the time-delay;
- G_{fr} ;
- proper local controllers.

It results that higher (TFR) values of G_{fr} can be imposed for a given T .

SCC - Experimental Verification

- Repetitive operator actions (force impulses) on the master,
- force reflection gain approximately equal to TFR.

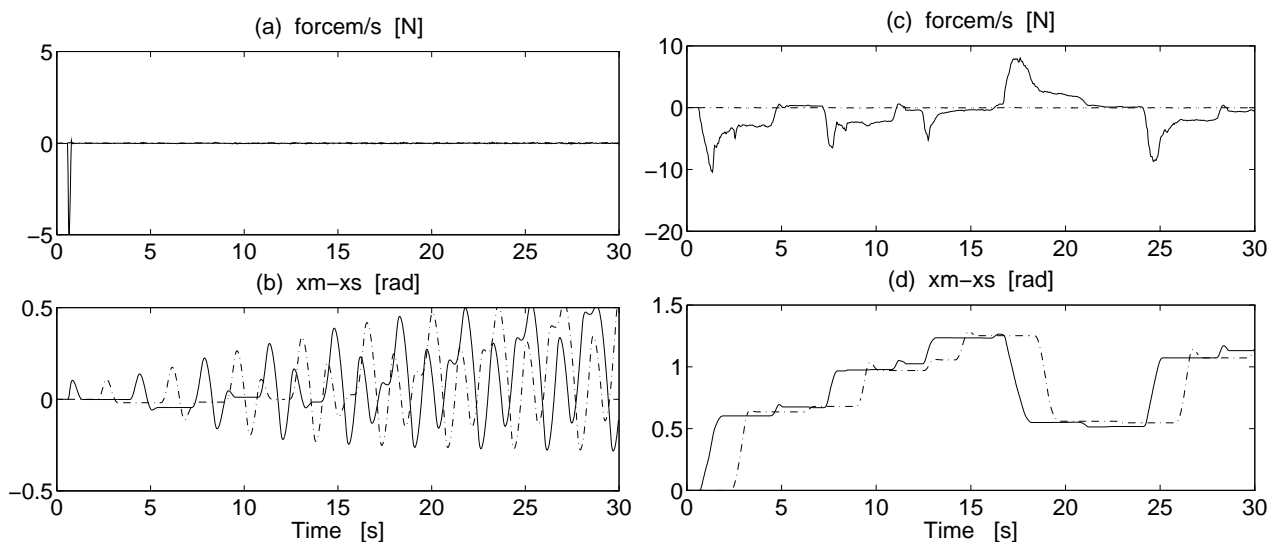
$$T = 0.1 \text{ s}$$



SCC - Experimental Verification

- Repetitive operator actions (force impulses) on the master,
- force reflection gain approximately equal to TFR.

$$T = 1.0 \text{ s}$$



- For a given time-delay, the force reflection gain G_{fr} can be larger than in the TFR scheme.
- For larger time-delays the force reflection gain should be accordingly reduced to guarantee stability.

SCC and phase-lag controller

In SCC teleoperation for a given time-delay T a proper limitation of the force reflection gain G_{fr} should be introduced.

For large time-delays the maximum G_{fr} assuring stability is noticeably reduced.

In order to increase the maximum G_{fr} value it is possible to introduce the following control law in the feedback flow of the teleoperator, in place of the G_{fr} gain:

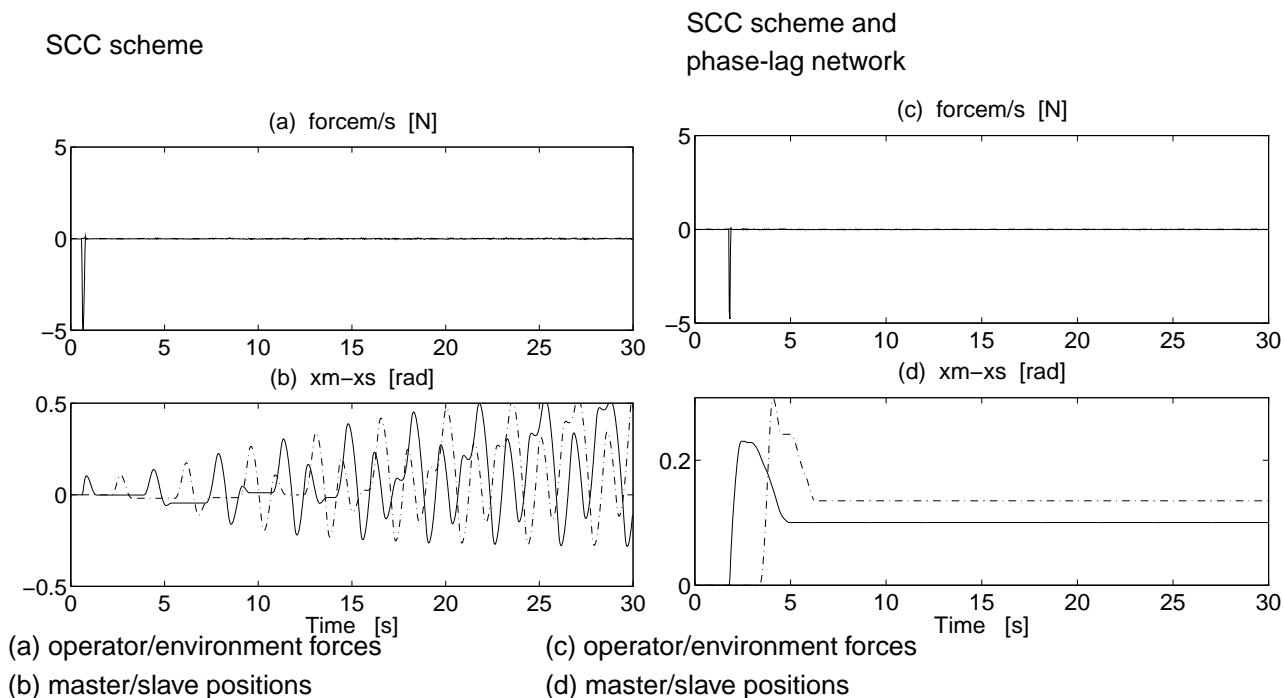
$$D(s) = G_{fr} \frac{1 + s/z}{1 + s/p}$$

The zero (z) and the pole (p) of the phase-lag network design can be based on frequency techniques (Michailov hodographs, Domain subdivision).

SCC and phase-lag controller

Experimental comparison between the original SCC scheme and the phase-lag scheme is shown.

- Approximately equal steady-state force reflection,
- similar initial operator force action on master, (in both cases time-delay $T = 1.0$ s).



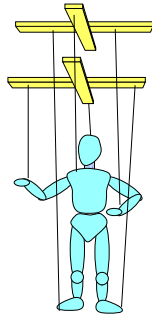
Robotic Telemanipulation:

Passive Control

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Passivity based teleoperation

Instabilities in time-delay teleoperation is produced by the non-passive features of the communication network (i.e. traditional force reflection).

Goal of passivity-based teleoperation is to obtain passivity for the communication network

$$\Rightarrow \text{stability} \forall \text{ time-delay } T$$

The communication channel is designed on the basis of the lossless transmission line and the electro-mechanical analogy.

Two control schemes have been introduced (Anderson & Spong, Niemeyer & Slotine) corresponding to different considered levels of complexity and phenomena:

1. the “*lossless transmission line*”,
2. the “*passivity-based with impedance adaptation*”.

Passivity based teleoperation - Lossless TL

The lossless transmission line is described by the two-port:

$$\begin{cases} \mathbf{f}_m(s) &= \tanh(sT) \dot{\mathbf{x}}_m(s) + \operatorname{sech}(sT) \mathbf{f}_s(s) \\ -\dot{\mathbf{x}}_s(s) &= -\operatorname{sech}(sT) \dot{\mathbf{x}}_m(s) + \tanh(sT) \mathbf{f}_s(s) \end{cases}$$

resulting in the hybrid matrix:

$$\mathbf{H}(s) = \begin{bmatrix} \tanh(sT) & \operatorname{sech}(sT) \\ -\operatorname{sech}(sT) & \tanh(sT) \end{bmatrix}$$

Passivity based teleoperation - Lossless TL

The scattering operator $\mathbf{S}(j\omega)$ is:

$$\mathbf{S}(j\omega) = \begin{bmatrix} 0 & e^{-j\omega T} \\ e^{-j\omega T} & 0 \end{bmatrix}$$

from which the following alternative representation of the lossless transmission is obtained:

$$\begin{bmatrix} \mathbf{f}_{md}(t) - \dot{\mathbf{x}}_m(t) \\ \mathbf{f}_s(t) + \dot{\mathbf{x}}_{sd}(t) \end{bmatrix} = \begin{bmatrix} \mathbf{f}_s(t - T) - \dot{\mathbf{x}}_{sd}(t - T) \\ \mathbf{f}_{md}(t - T) + \dot{\mathbf{x}}_m(t - T) \end{bmatrix}$$

- In real application a scaling (impedance) should be introduced in the previous equations between velocities and forces.
- Introduction of scaling factors between velocities and forces should be carefully considered in order to maintain the passivity of the network.
- Introduction of scaling without altering the passivity properties is obtained by means of two transformers (passive two-port elements) at both the master and the slave site.
- The two transformers should introduce respectively the scaling factors:

master transformer ratio	B
slave transformer ratio	$1/B$

B is the *Characteristic Impedance* of the communication network.

A proper selection of B is essential in order to exploit the performances of the device.

Passivity based teleoperation - Lossless TL

The resulting network is:

$$\begin{cases} \mathbf{f}_{md}(t) = \mathbf{f}_s(t - T) + B[\dot{\mathbf{x}}_m(t) - \dot{\mathbf{x}}_{sd}(t - T)] \\ \dot{\mathbf{x}}_{sd}(t) = \dot{\mathbf{x}}_m(t - T) + \frac{1}{B}[\mathbf{f}_{md}(t - T) - \mathbf{f}_s(t)] \end{cases}$$

The introduction of the characteristic impedance of the communication network results in the re-definition of the wave variables:

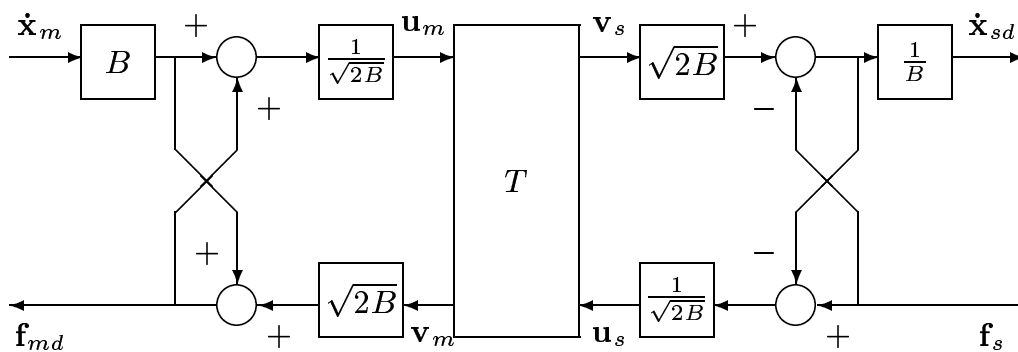
$$\begin{aligned} \mathbf{u}_m &= \frac{1}{\sqrt{2B}}(\mathbf{f}_m + B\dot{\mathbf{x}}_m) & \mathbf{u}_s &= \frac{1}{\sqrt{2B}}(\mathbf{f}_s - B\dot{\mathbf{x}}_s) \\ \mathbf{v}_m &= \frac{1}{\sqrt{2B}}(\mathbf{f}_m - B\dot{\mathbf{x}}_m) & \mathbf{v}_s &= \frac{1}{\sqrt{2B}}(\mathbf{f}_s + B\dot{\mathbf{x}}_s) \end{aligned}$$

By considering the wave variables in place of the power ones, the alternative description of the communication network is obtained:

$$\begin{cases} \mathbf{f}_{md}(t) = B \dot{\mathbf{x}}_m(t) + \sqrt{2B} \mathbf{v}_m(t) \\ \dot{\mathbf{x}}_{sd}(t) = -\frac{1}{B} [\mathbf{f}_s(t) - \sqrt{2B} \mathbf{v}_s(t)] \end{cases}$$

Passivity based teleoperation - Lossless TL

Therefore, the following transmission line is obtained:



Impedance adaptation

Impedance mismatches are present at the extremities of the communication line, originating *Power Reflections* at both sites of the teleoperation system.

The non-strict passivity (note that $\|\mathbf{S}(j\omega)\| = 1.0$) of the lossless transmission line does not introduce dissipation for the possible power reflections, destabilizing the device.

Impedance adaptation at the terminations of the line is possible by means of two admittance/impedance elements whose values are tuned with the characteristic impedance of the line B :

master termination	admittance	$1/B$
slave termination	impedance	B

Impedance adaptation

The time descriptions of the adaptation elements are:

$$\begin{cases} \dot{\mathbf{x}}'_m(t) &= \dot{\mathbf{x}}_m(t) - \frac{1}{B}\mathbf{f}_{md}(t) \\ \mathbf{f}'_s(t) &= \mathbf{f}_s(t) + B\dot{\mathbf{x}}_{sd}(t) \end{cases}$$

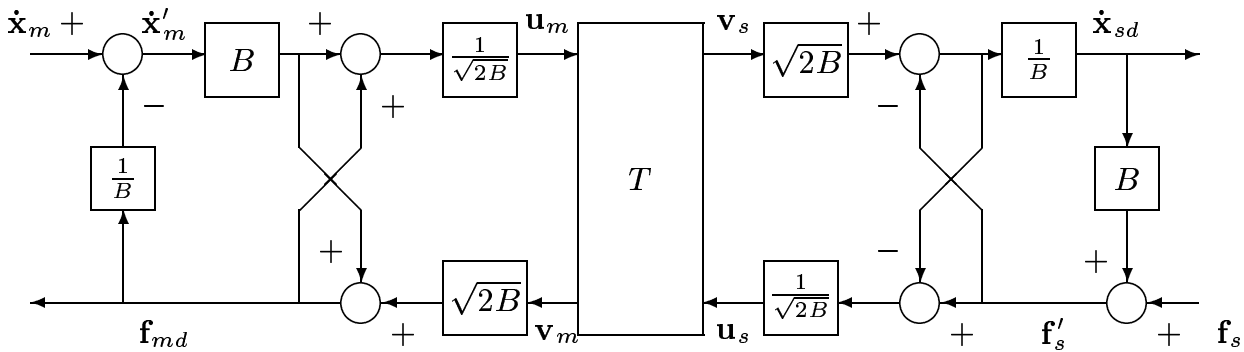
$\dot{\mathbf{x}}'_m$ and $\mathbf{f}'_s(t)$ being the new input variables of the communication line.

The insertion of these elements results in the modification of the stability features of the network as well as of its description:

$$\begin{cases} \mathbf{f}_{md}(s) &= \frac{B}{2}\dot{\mathbf{x}}_m(s) + \frac{1}{2}e^{-sT}\mathbf{f}_s(s) \\ \dot{\mathbf{x}}_{sd}(s) &= \frac{1}{2}e^{-sT}\dot{\mathbf{x}}_m(s) - \frac{1}{2B}\mathbf{f}_s(s) \end{cases}$$

Impedance adaptation

A scheme representing the two adaptation elements at the terminations of the communication line is:



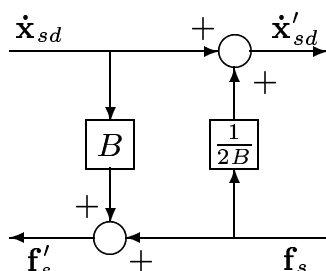
Impedance adaptation

Considering the previous power variable description of the network

$$\begin{cases} \mathbf{f}_{md}(s) &= \frac{B}{2} \dot{\mathbf{x}}_m(s) + \frac{1}{2} e^{-sT} \mathbf{f}_s(s) \\ \dot{\mathbf{x}}_{sd}(s) &= \frac{1}{2} e^{-sT} \dot{\mathbf{x}}_m(s) - \frac{1}{2B} \mathbf{f}_s(s) \end{cases}$$

the following considerations can be drawn:

- termination elements introduce not unitary scaling factors in the system equation (effect not present in the non-adapted network),
- power modification in the network results in the presence of a position drift between master and slave variables when the slave is interacting with the environment, i.e. when $\mathbf{f}_s \neq 0$ (or transient phases),
- a scheme for the compensation of this effect can be obtained by adding the following further element at the slave site.

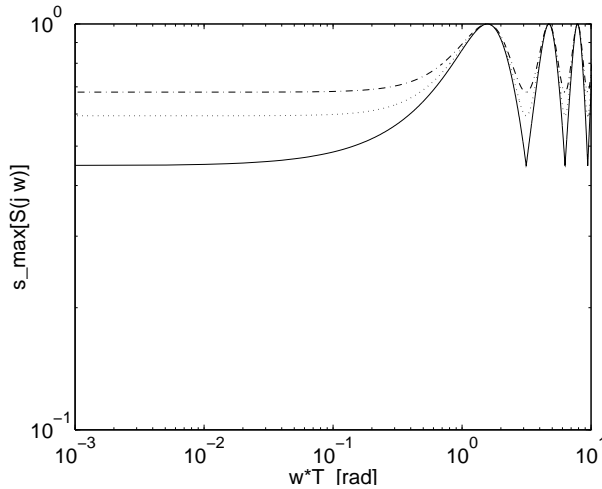


$$\dot{x}'_{sd}(s) = \frac{1}{2} e^{-sT} \dot{x}_m(s)$$

Scattering Analysis

Maximum singular value $\sigma \{ \mathbf{S}(j\omega) \}$ of the scattering matrix of passivity based teleoperation scheme is given:

- as a function of ωT ,
- for different values of the force reflection gain G_{fr} .

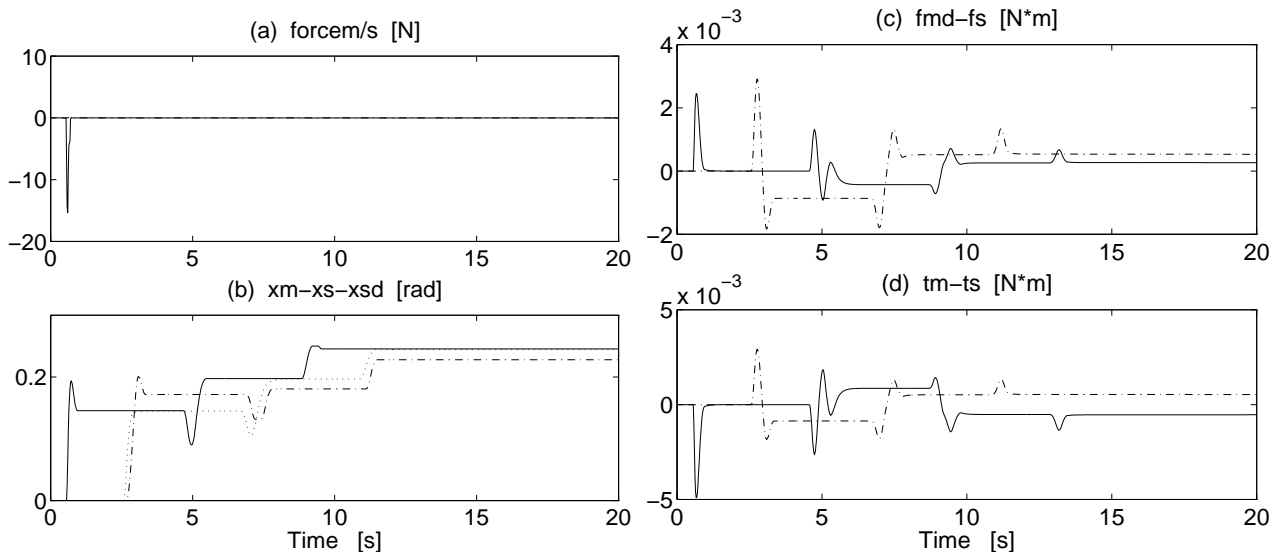


- $G_{fr} = 0.5$ (dashdot),
- $G_{fr} = 1.0$ (solid),
- $G_{fr} = 1.5$ (dotted).

- The system is passive (even if not strictly passive) for any G_{fr} value.
- The introduction of the drift compensation schemes does not alter the passivity of the network.

Experimental Verification

- Adapted passivity based teleoperation,
- operator action (force pulse) on the master,
- time-delay $T = 1.0$ s.

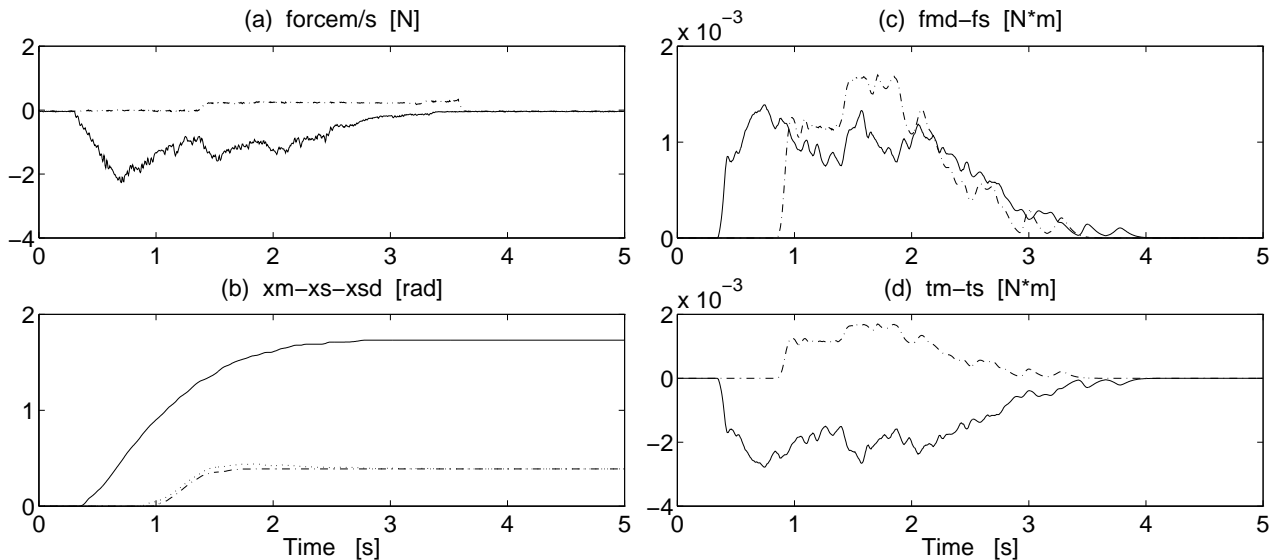


(a) operator/environment forces
(b) master/slave positions

(c) master/slave forces
(d) master/slave torques

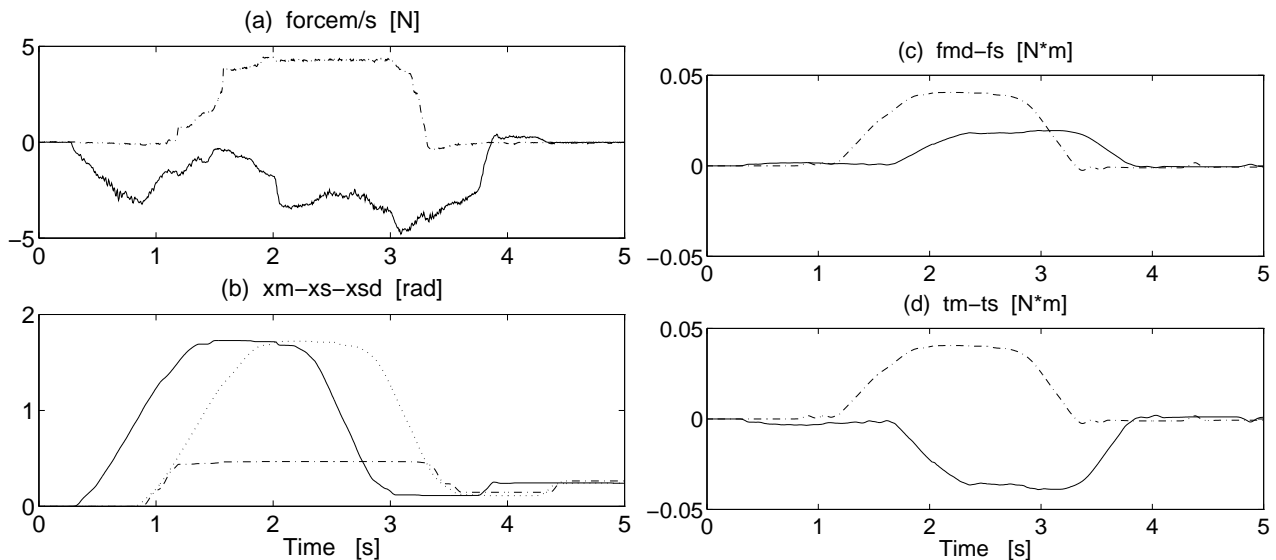
Position Drift

- Adapted passivity based teleoperation,
- operator action on the master,
- interaction with the environment,
- position drift between master and slave (no use of drift compensation algorithm),
- time-delay $T = 0.5$ s.



Position Drift

- Introduction of the position drift compensation algorithm:
- time-delay $T = 0.5$ s.



PREDICTIVE CONTROL: the task is graphically simulated in real-time, without time-delay, exploiting a model of the remote environment and of the slave device. A graphic interpace is used on which the robotic device is superimposed on the real operating system in the scene of the remote site.

This type of task planning helps when a noticeable time-delay occurs. In fact, when operators deal with relevant time-delays, usually they operate with a “move and wait” strategy, specifying small displacements to the remote robot. With predictive control this is avoided.

On the other hand, the operator has only visual information about the remote environment and the task execution.

The force information may or may not be transmitted to the operator, and an extensive use of graphic simulation and *telesensor programming* is made to help control of the task execution.

In the ROTEX project, this control approach has been adopted.

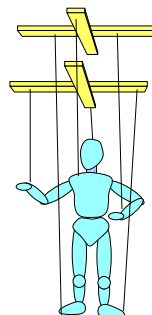
By using predictive display, the time required to execute complex tasks is greatly reduced.

Robotic Telemanipulation: Performances

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Evaluation criteria for teleoperated systems

Performances of master/slave teleoperation devices depend on:

- mechanical structure of the robotic systems,
- local controllers,
- methodology used for their coordination.

Performance measures of teleoperators can be obtained with respect to several criteria, related to a number of different definitions proposed in the literature of what an “ideal telemanipulator” should be, both in the time or frequency domain.

Examples may be:

- total task completion time,
- time integral of the applied forces or of the norm of the position/force errors,
- dexterity measures,
- ...

In the computation of some of these measures also the dynamics of the local and remote systems have to be taken into account: usually it is desired to express the performances of the overall device as perceived by the operator.

This means that the dynamics of the environment must be included. For this reason, a second-order model is often assumed:

Evaluation criteria for teleoperated systems

TIME TO COMPLETION:

Given a particular task, the time to completion is defined as the elapsed time from its start (t_i) to its completion (t_f)

$$T_c = t_f - t_i$$

This index has been extensively used to evaluate stereo-vision systems and to assess workload and task learning.

The computation of this index is quite simple in well defined tasks, such as in laboratory experiments, while it results more difficult in other circumstances.

With this criterion, a system is “good” if the time it requires for executing a task is the minimum. A drawback is that this criterion does not provide any information about the quality of the execution.

Evaluation criteria for teleoperated systems

OPERATOR SUBJECTIVE ASSESSMENT:

This criterion clearly depends on the personal judgement of the operator, and therefore it may not be regarded as an absolute index.

However, it has been shown that this criterion may be definitely correlated with other performance measures, e.g. time to completion, and that it takes into account more complex information not easily measurable in other manners.

EFFORT-BASED CRITERIA:

Although several indices based on the energy consumption required to execute a particular task have been proposed, it was found that a simple measure of the average of the absolute changes in joint displacements per period of measurement is as informative about the performances of a teleoperator as more complex effort functions. Assuming a constant period of measure:

$$\mathcal{E} = \frac{\sum_{i=1}^p \sum_{j=0}^{n-1} w_j |dq_j^i|}{pn}$$

p is the number of periods, dq_j^i is the displacement of joint j in the i -th period, and w_j is a proper weight factor.

A similar index could be defined considering task variables instead of joint variables.

Evaluation criteria for teleoperated systems

DEXTERITY:

This type of measure is related to the kinematic configuration and to the posture of the manipulators.

In fact, tasks in the velocity or force domain can be performed with different efficiency depending on the configuration of the robotic arm. Basically, measures of this type are extensions to telemanipulators of known manipulability indices for industrial arms, mostly based on the Jacobian matrix $\mathbf{J}(\mathbf{q})$ of a given robot.

Examples:

- the determinant of \mathbf{J} , $\det(\mathbf{J})$;
- the minimum singular value $\sigma_{min}(\mathbf{J})$;
- the condition number of \mathbf{J} , $\sigma_{max}(\mathbf{J})/\sigma_{min}(\mathbf{J})$;
- the “manipulability ellipsoids”, and so on.

Evaluation criteria for teleoperated systems

PERFORMANCE EVALUATION BASED ON THE HYBRID MATRIX

A direct manner to evaluate the performances of a telemanipulation system is to compare its hybrid matrix \mathbf{H} to the ideal one \mathbf{H}_{ideal} .

A performance index can be defined as the “distance” between these two matrices:

$$d = \sum_{i,j} w_{ij} |h_{ij} - h_{ideal,ij}|$$

In the computation of the hybrid matrix $\mathbf{H}(s)$ all the dynamics relating the operator to the environment (i.e. the master with its controller, the communication line, the slave and the environment) have to be considered.

If one takes into consideration, for example, only the hybrid matrix of the communication line, misleading results may be obtained.

Evaluation criteria for teleoperated systems

PERFORMANCE INDICES:

This criterion is based on the definition of *ideal responses* of the teleoperation system, in terms of time-behaviour of positions and forces.

Assuming that an input force \mathbf{f}_{op} is applied to the master by the operator, three ideal responses are considered:

- **ideal response 1:** the slave position $\mathbf{x}_s(t)$ follows exactly the master position $\mathbf{x}_m(t)$ (i.e. $\mathbf{x}_s(t) = \mathbf{x}_m(t)$) for any dynamics of the manipulated object;
- **ideal response 2:** the slave force $\mathbf{f}_s(t)$ is equal to the master one $\mathbf{f}_m(t)$ ($\mathbf{f}_s(t) = \mathbf{f}_m(t)$) for any dynamics of the manipulated object;
- **ideal response 3:** both the slave position and force variables are equal to the master ones for any dynamics of the manipulated object.

Evaluation criteria for teleoperated systems

The performance indices are defined according to the ideal responses 1, 2, and 3 as

$$\begin{aligned} J_p &= \int_0^{\omega_{max}} \|G_{mp}(j\omega) - G_{sp}(j\omega)\| \|W(j\omega)\| d\omega \\ J_f &= \int_0^{\omega_{max}} \|G_{mf}(j\omega) - G_{sf}(j\omega)\| \|W(j\omega)\| d\omega \end{aligned} \quad (5)$$

where ω_{max} defines the frequency range of interest, and $G_{mp}(j\omega)$, $G_{sp}(j\omega)$, $G_{mf}(j\omega)$ and $G_{sf}(j\omega)$ are the transfer functions from the input (i.e. the force applied by the operator) to the master position, slave position, master force and slave force respectively.

A function (for example a first-order filter) $W(j\omega)$ is introduced in the indices J_p , J_f for weighting different frequencies components.

From the definitions, it is clear that the measures provided by the indices represent distances between slave and master positions (J_p) and forces (J_f).

- When the system realises the ideal response 1, then $J_p = 0$.
- When the system realises the ideal response 2, $J_f = 0$.
- For teleoperation systems satisfying the ideal response 3, both J_p and J_f are zero.