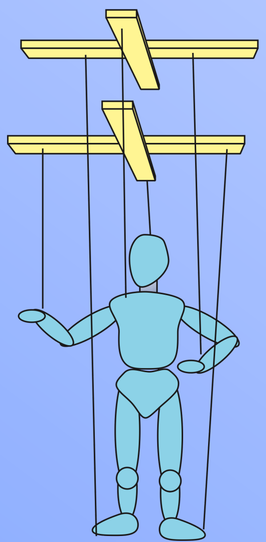
Robotica Industriale LM

ROBOTIC TELEMANIPULATION: Modelling and Control Aspects



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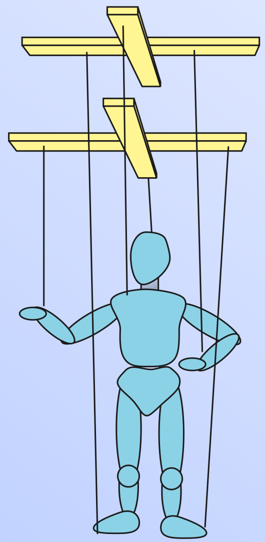
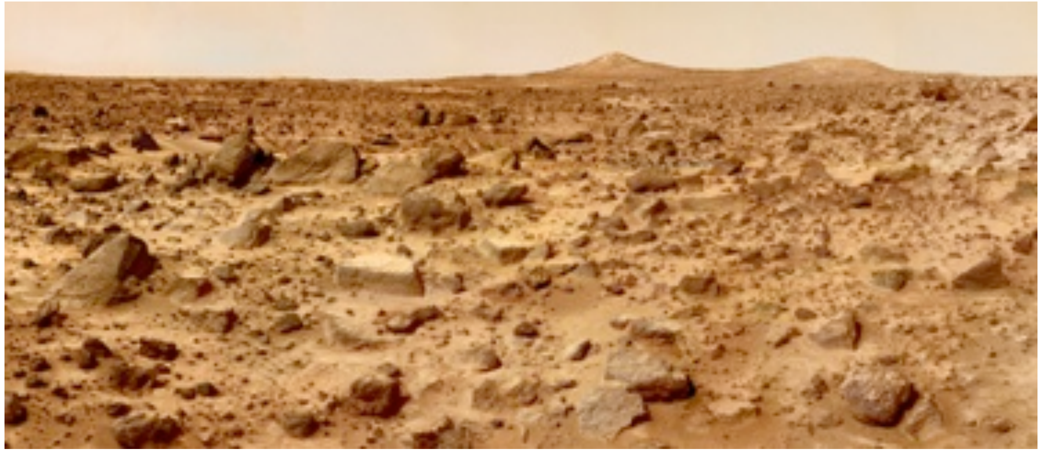


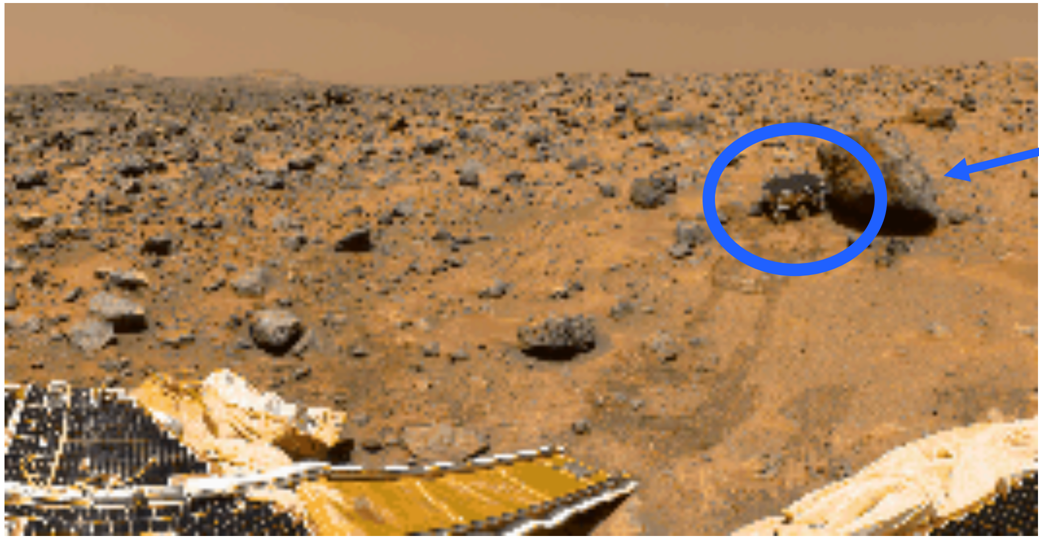
Telerobotics:

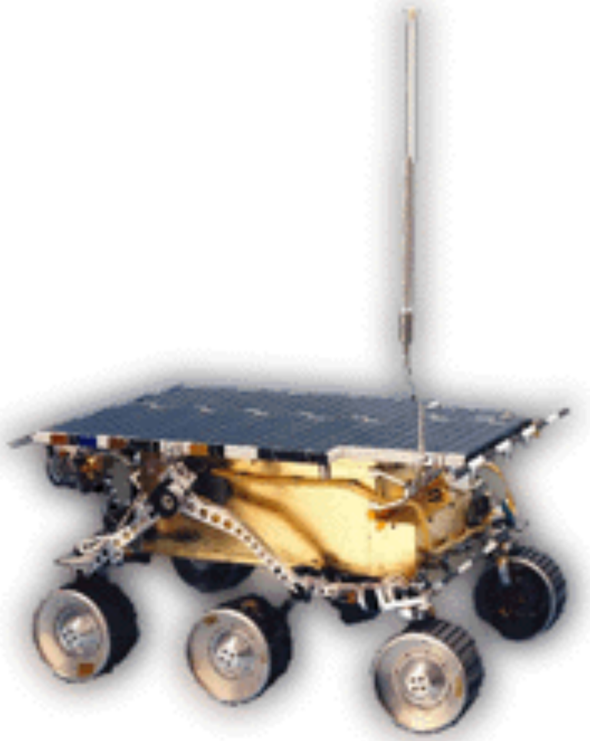
some "recent" achievements…

Telerobotics – 1993: Rotex

Telerobotics – 1997: Mars Pathfinder



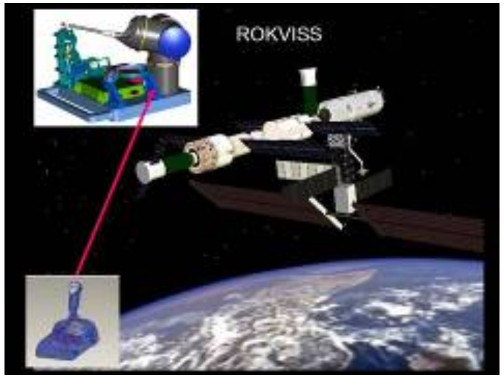


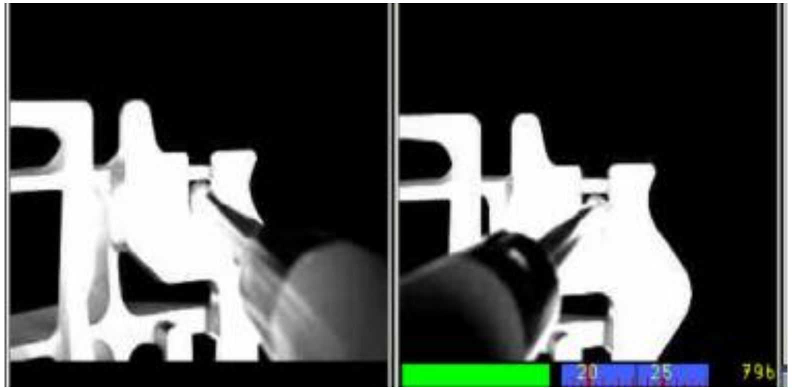


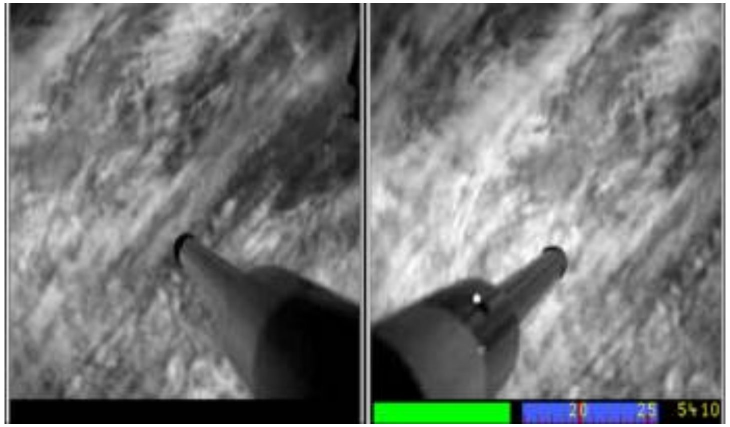
Telerobotics – 2001: Telesurgery

First trans-oceanic surgery operation
(New York, USA – Strasbourg, F), Prof. Marescaux

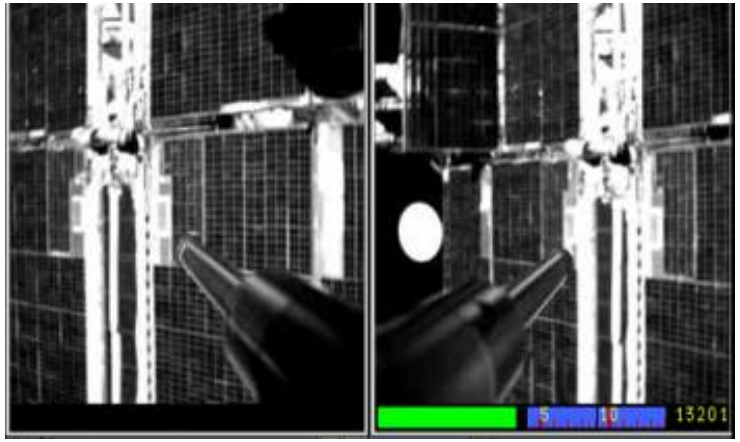
Telerobotics – 2005: Rockviss



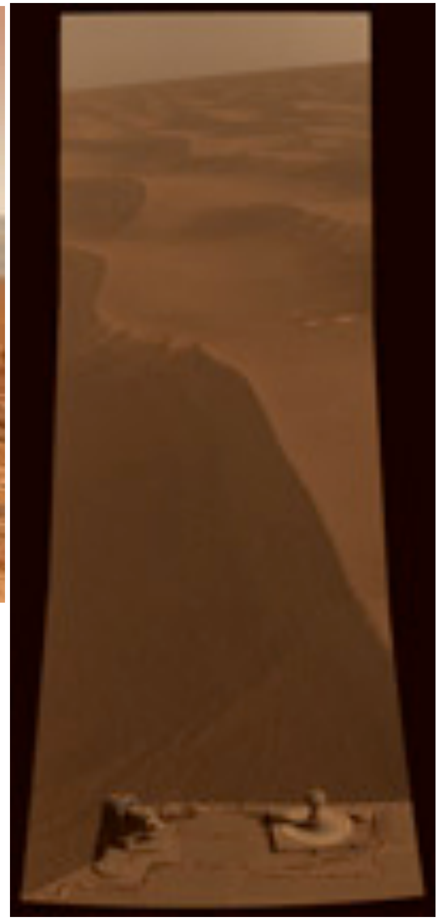


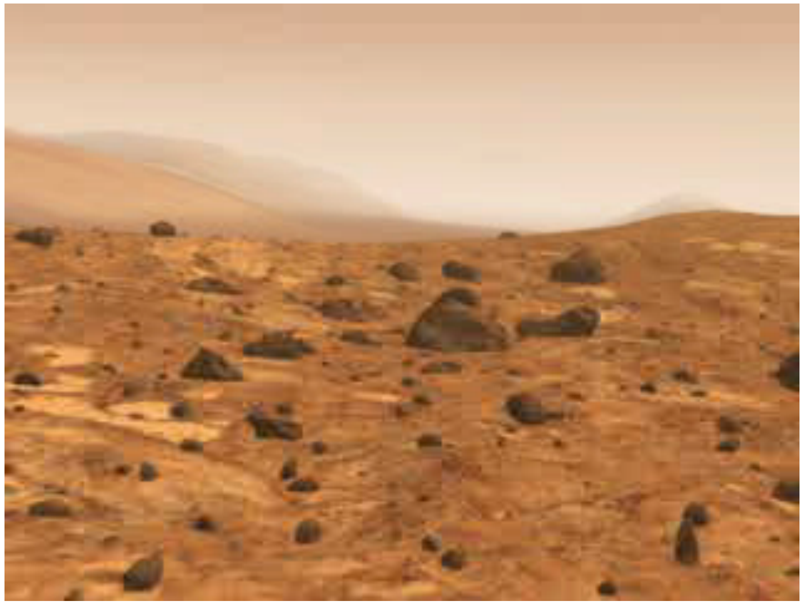


movie



Telerobotics – 2004: Mars Rovers





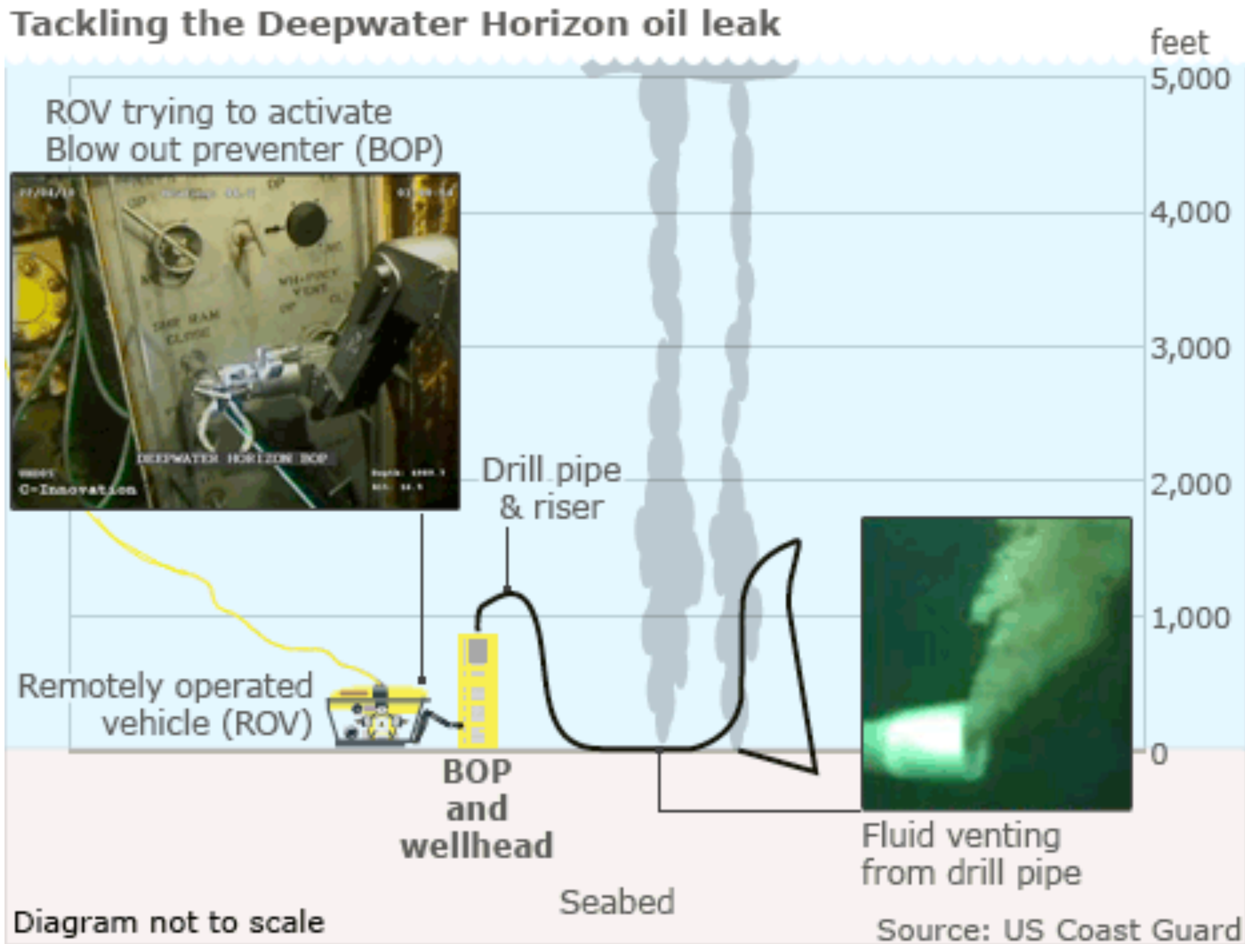
NASA-JPL Rovers SPIRIT & OPPORTUNITY
Launched: June/July 2003
Landed: January 2004

Still working…
June 29 2010

http://marsrovers.jpl.nasa.gov/

Robots Work to Stop Leak of Oil in Gulf

… BP - which is responsible under federal law for the clean-up - said it was using four submersible vehicles, equipped with cameras and remote-controlled arms, to try to activate a blow-out preventer - a series of pipes and valves that could stop the leak …



Summary

- Telerobotics: A brief history
- Control problems in telerobotics
- Modelling a telemanipulation systems
- Control schemes
- Comparison criteria
- Conclusions

Development of different “**TELE**-technologies":

- **TELE-scope**: capability of observing from distance

  1593, De Refractione, Galileo Galilei

- **TELE-graphy**: capability of writing from distance

  1833 Samuel Morse - and even before (1753 C. Morris and others);

  RADIO: 1896 Guglielmo Marconi;

- **TELE-phony**: capability of talking from distance

  1849, 1871 Antonio Meucci;
  1876, Bell, Gray;

- **TELE-vision**: capability of seeing from distance

  1900 the word “television” is first used;
  1928 first commercial mechanical TV;
  1941 first commercial electronic B&W TV;

These technologies provide knowledge at a distance

Telerobotics: a brief history

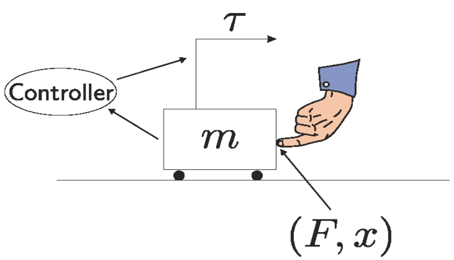
Development of different "**TELE**-technologies":

- **TELE-operation**: capability of performing remote manipulation
  1940-1950 Raymond C. Goertz (Argonne Nat. Lab., where E. Fermi developed the first nuclear reactor)

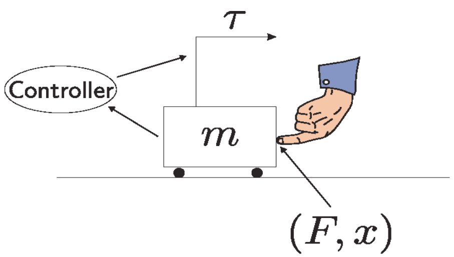
This technology provides physical interaction capability at a distance

Development of different "**TELE**-technologies":

Information interaction
limited amount of energy exchange



Energetic interaction
mechanical energy
is actually exchanged

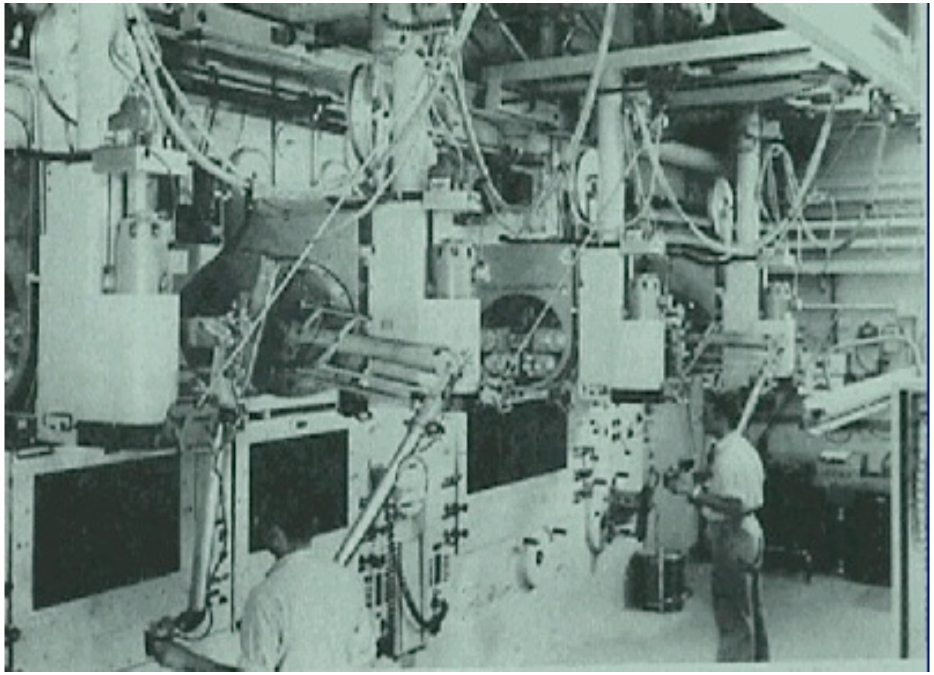


Paynter, "Generalized System Theory", 1961

Telerobotics: a brief history

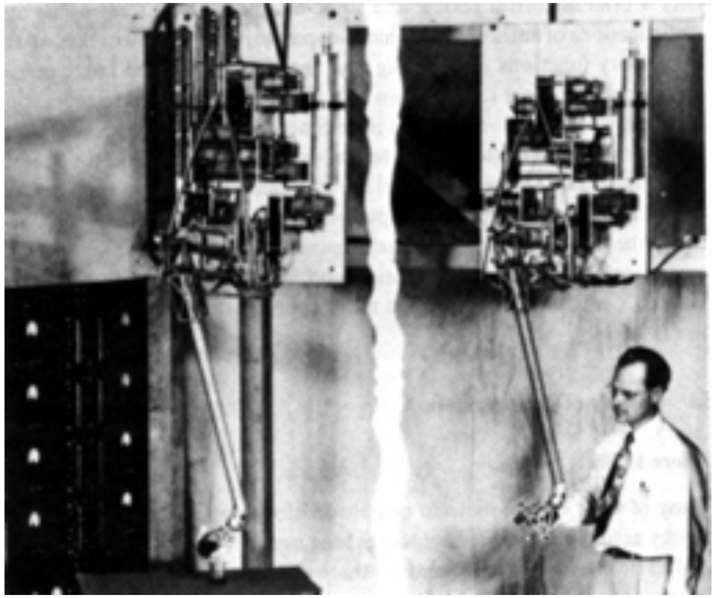
In robotics, teleoperation is one of the first fields to be developed:

Applications (nuclear, medicine) are dated back to the late 40s.



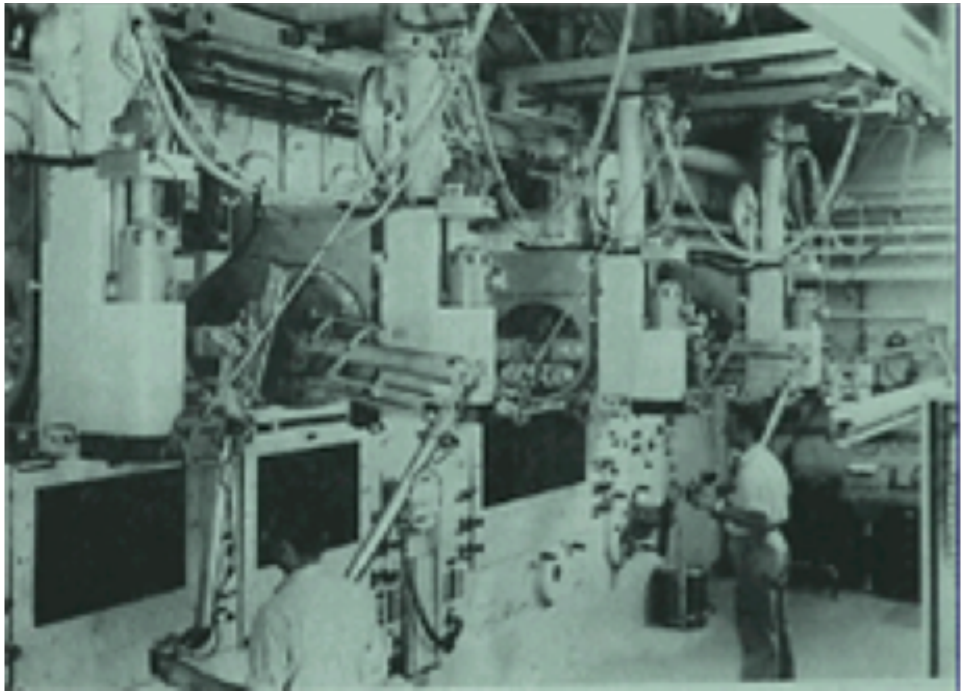
Telerobotics: a brief history

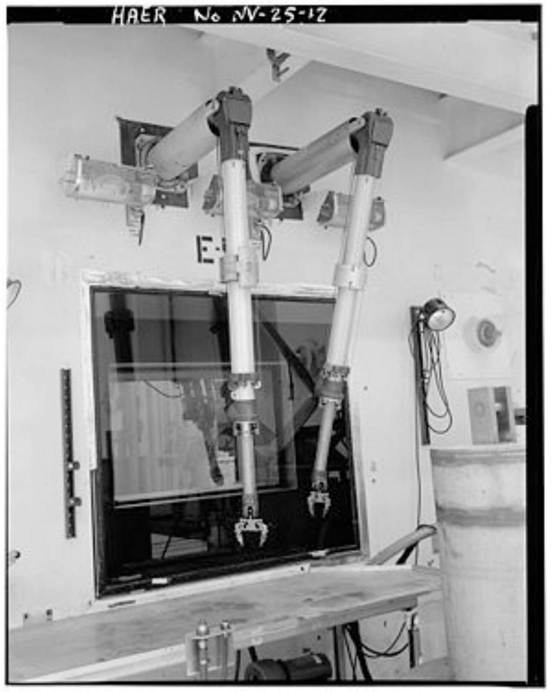
- **< 1600:** very simple devices designed as arm extensions;
- **early 1900:** crude teleoperators for earth moving, constructions, and related tasks;
- **'40s:** human limb prostheses (arm hooks activated by the parts of the human body);
- **about 1945:** first master-slave teleoperator (mechanical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



Telerobotics: a brief history

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





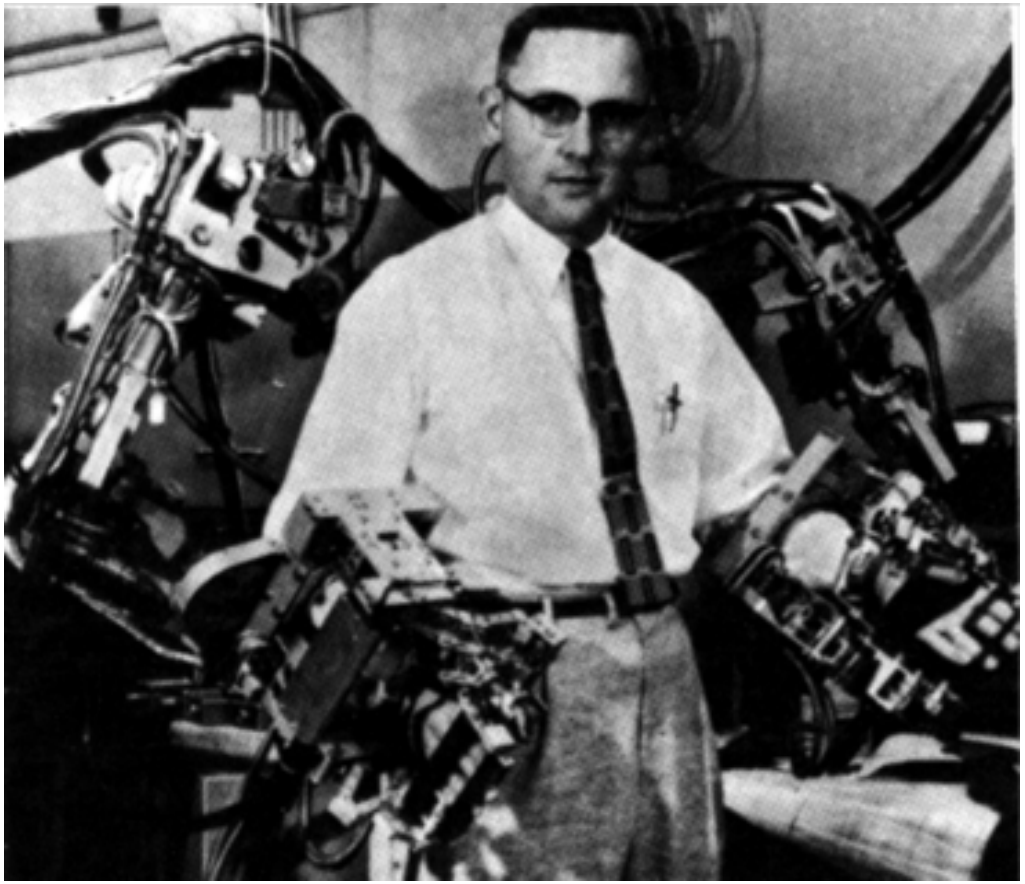
Telerobotics: a brief history

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

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

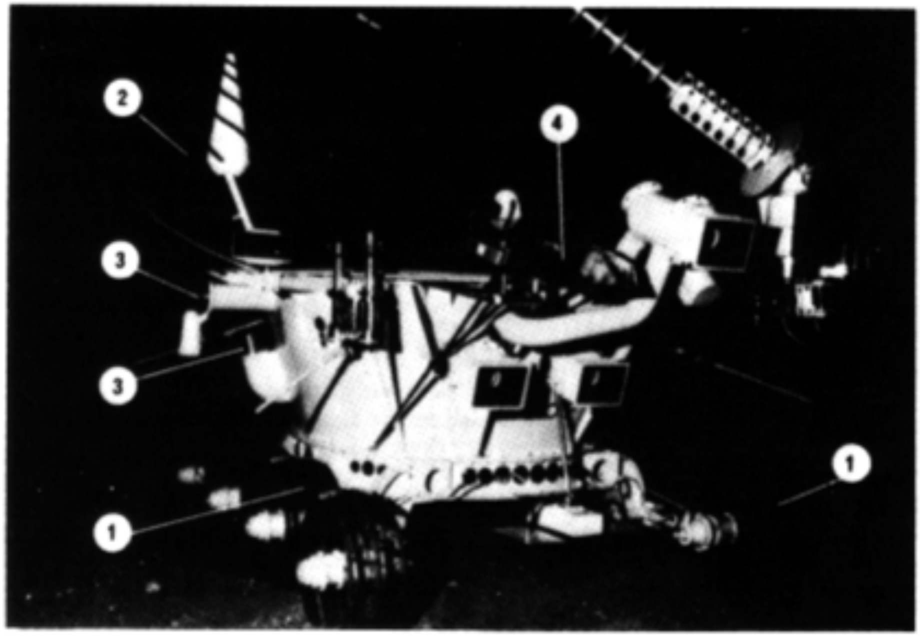
Telerobotics: a brief history

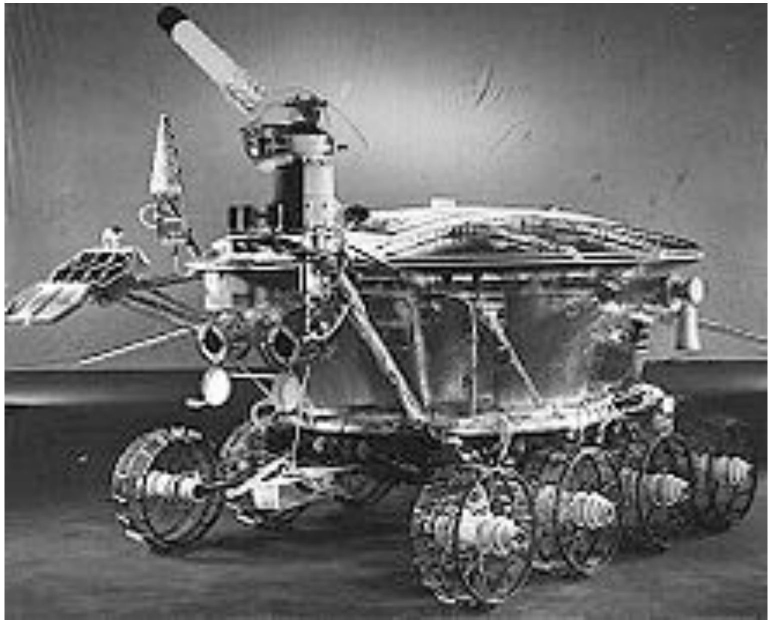
- **60s:** Telepresence, force reflection, two-arm teleoperators. touch sensing and display, a significant example is the Mosher's Handyman, developed at General Electric Co.;



Telerobotics: a brief history

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

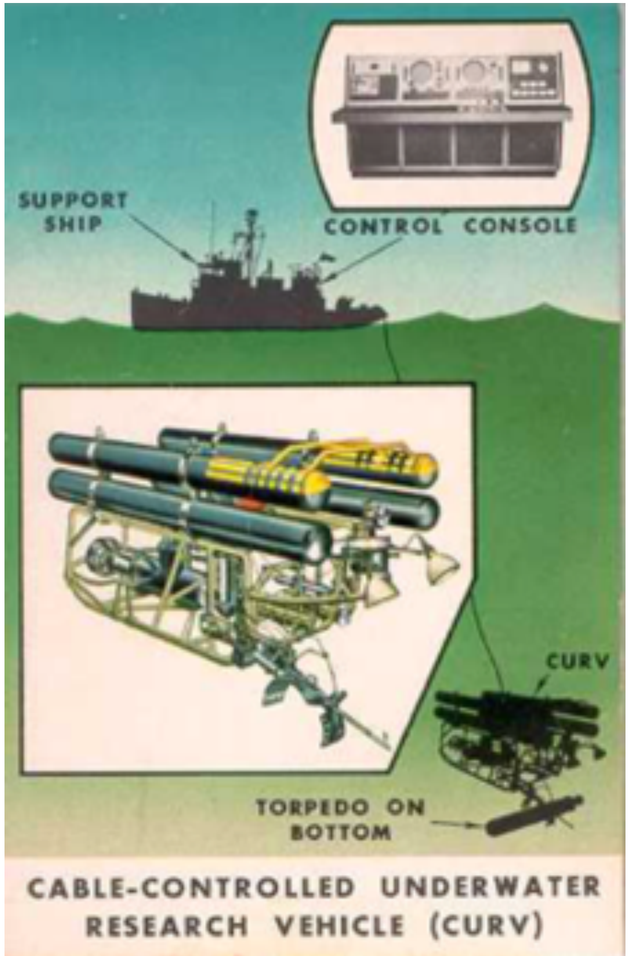




Lunokhod (USSR): landed on Moon in 1971
It was intended to work for 3 lunar days (approx 3 months) but actually operated for almost 11 lunar days!

Telerobotics: a brief history

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



Telerobotics: a brief history

- **80s:** extensive use of ROVs (Remotely Operated Vehicles) in offshore operations for oil/gas industry

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

Telerobotics: a brief history

- **1982:** The first force-reflecting telerobotics system, which used distributed electronics, was the Central Research Laboratory Model M2 from 1982. It has been developed together with the Oak Ridge National Laboratory and was used for some time for demonstration tasks including military, space or nuclear applications. The M2 system was used by NASA to simulate the ACCESS space truss assembly.

Telerobotics: a brief history

- **80s:** JPL ATOP Control Station (early 1980s). For space applications a dual-arm force reflecting telerobotic system had been developed by Bejczy et al. at JPL.

  For the first time kinematically and dynamically different master and slave systems are used, requiring control in Cartesian space coordinates.

Master devices

Telerobotics: a brief history

Some recent important tele-robotics examples:

- **April ’93:** the space robot ROTEX was flown on space-shuttle COLUMBIA (STS 55). A multisensory robot on board the spacecraft successfully worked in several modes teleoperated by astronauts, as well as in different telerobotic ground control modes.

- **July ’97:** the rover Sojourner landed on Mars in the Ares Vallis. From landing until the final data transmission on September 27, 1997, Mars Pathfinder returned 2.3 billion bits of information (more than 20,000 images, more than 15 chemical analyses, and extensive data on winds and other weather factors).

- **Sept. ’98:** first robotic cardio-surgical operation (Prof. Boyd).

- **June ’01:** the first trans-oceanic telesurgery operation (New York, USA – Strasbourg, F) (Prof. Marescaux)

Telerobotics: a brief history

Telemanipulators, in the broader sense of the terminology, have been developed since early 50s for use in a number of different areas.

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

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






Telerobotics: Space applications

Robots are used in space for:

- exploration,
- scientific experiments,
- commercial activities.

Main reasons of using robots in space are:

- Reducing the risks for astronauts,
- 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. However, for planetary missions, autonomous telerobots are required: the operator will have only a supervisory control of the task.

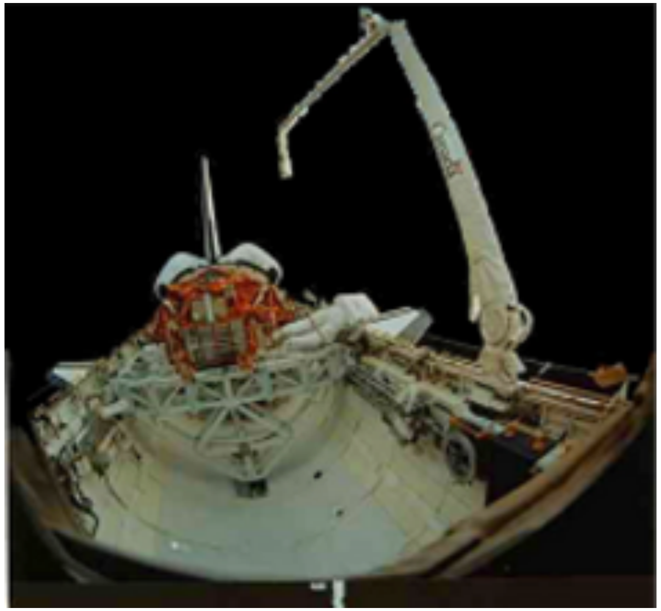
Main directions of current research activity are the development of:

- Arms for intra-vehicular and extra-vehicular activities (ESA, NASA, ...),
- Free flying platforms,
- Planetary rovers
- "Back to the Moon" (?)

Telerobotics: Canadian Remote Manipulator System - RMS

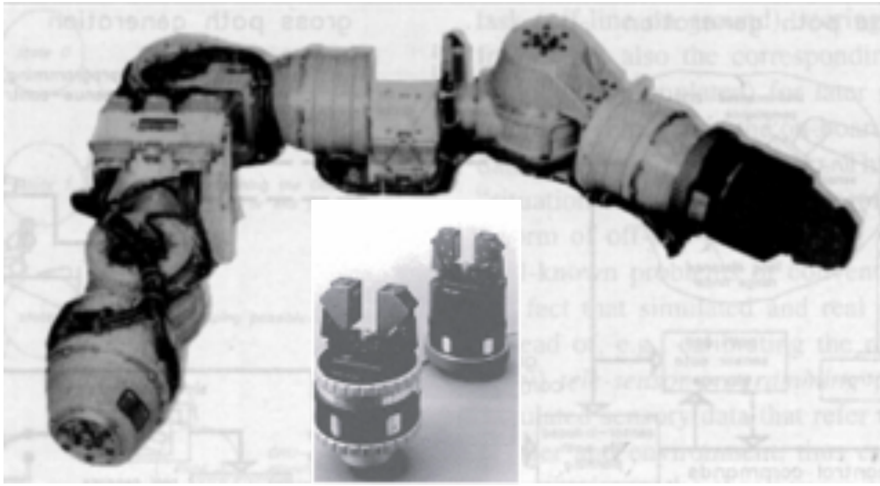
The arm installed on the US space-shuttle, the Canadian Remote Manipulator System (RMS), is probably the most known example of space telemanipulator:

- built by MD Robotics (Canada)
- 6 dof arm
- 11 meter long flexible structure
- able of executing pre-programmed and/or teleoperated tasks
- resolved rate control



Telerobotics: Rotex

- ROTEX: robotic arm for intra-vehicular activities developed by DLR, Germany. It was successfully used in the mission of the shuttle COLUMBIA in 1993, performing three 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
- sophisticated MMI with 3D stereo computer graphics, voice input/output, stereo imaging
- predictive control
- the master system is the “DLR control-ball” (6-axis force sensor)

Telerobotics: Space Servicing

SPIDER arm

Canadian Arm

Dextrous grippers

Robonaut

Movie 1

Movie 2

Telerobotics: Rockviss

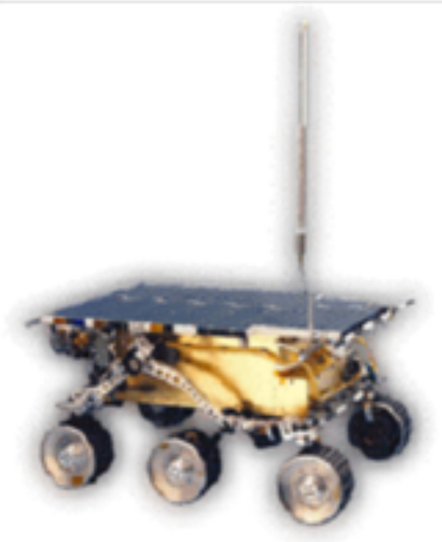
- Rockviss has been developed by DLR (ESA) for EVA activities on ISS

Telerobotics: Space Rovers

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

The NASA rovers SOJOURNER (mission Pathfinder, 1997), SPIRIT and OPPORTUNITY (January 2004) are probably the most known example of space rovers.

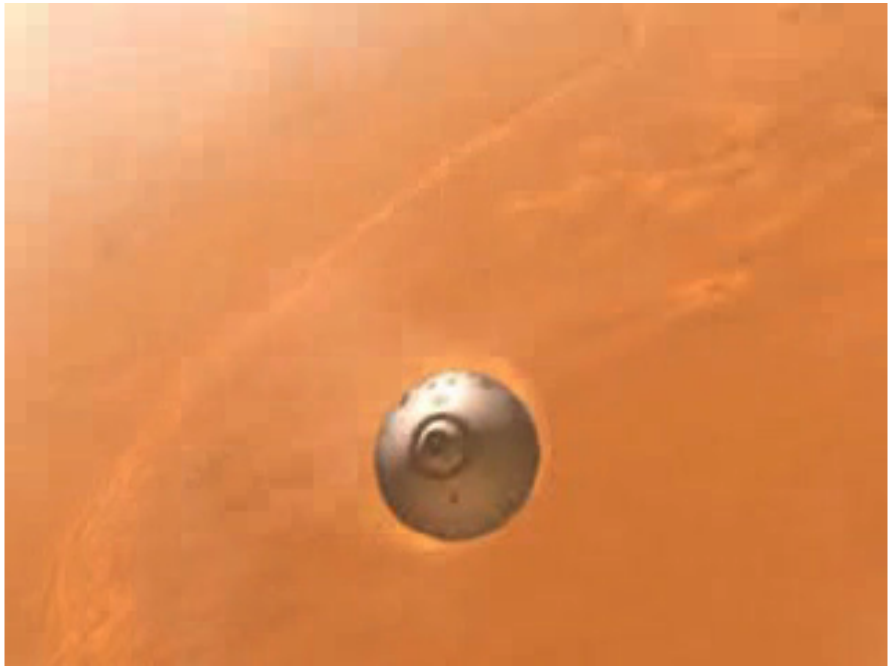
- Current technology would allow further substantial developments, which are slowed down by the large amount of money and time required to guarantee a successful mission.
- For these reasons the research are in general jointly developed by national space agencies, industries and research laboratories.



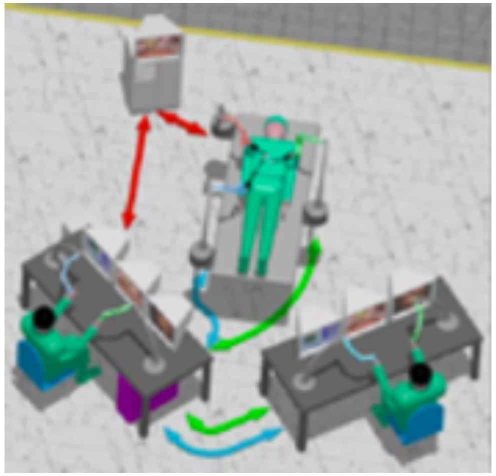
Telerobotics: Space Rovers

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).

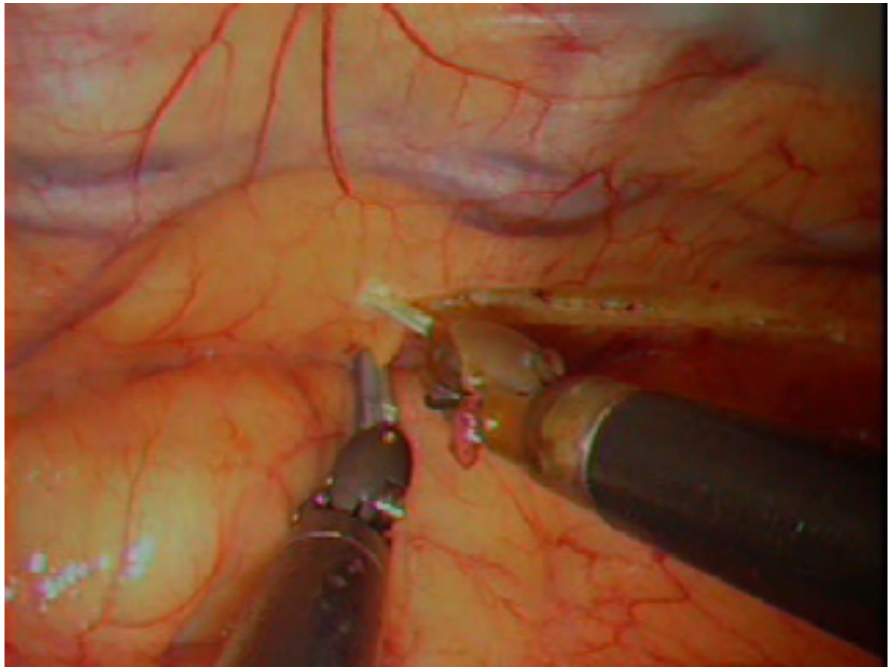


Telerobotics: Medical applications



Main applications of robotic manipulators in the medical field:

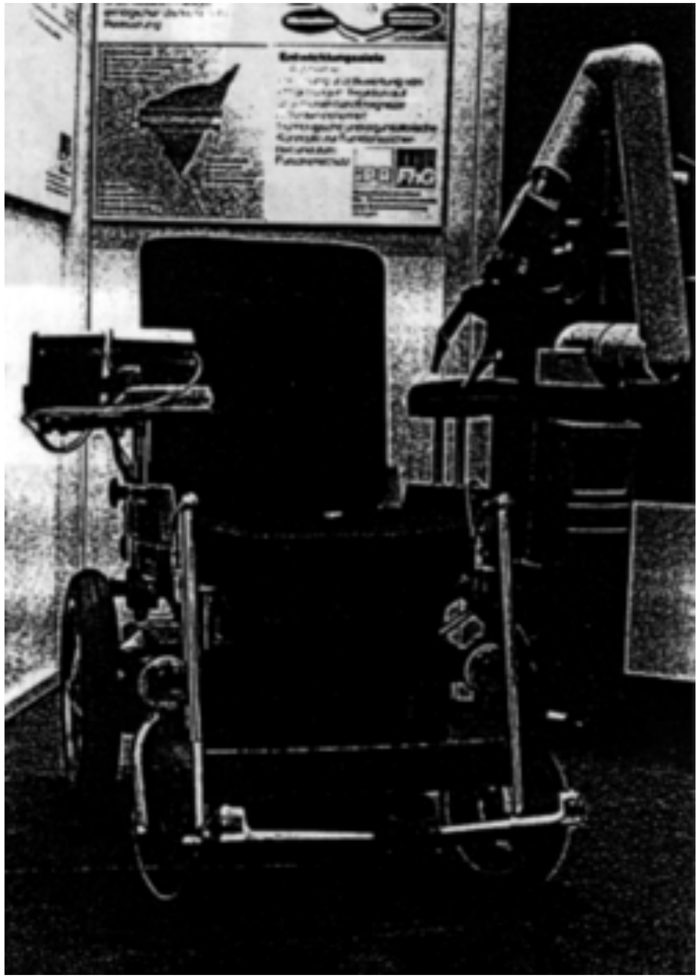
- help to impaired people,
- surgery operations,
- diagnose illnesses or injuries,
- training of specialized personnel.



Telerobotics: Medical applications

- 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.



Telerobotics: Medical applications

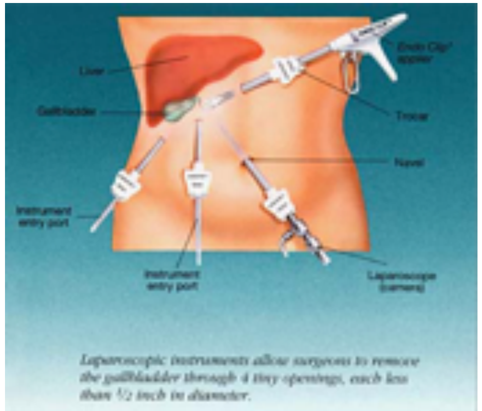
- At the moment, there is a relevant interest in applying teleoperated devices in microsurgery operations, e.g. eye surgery, where small precise movements are needed.

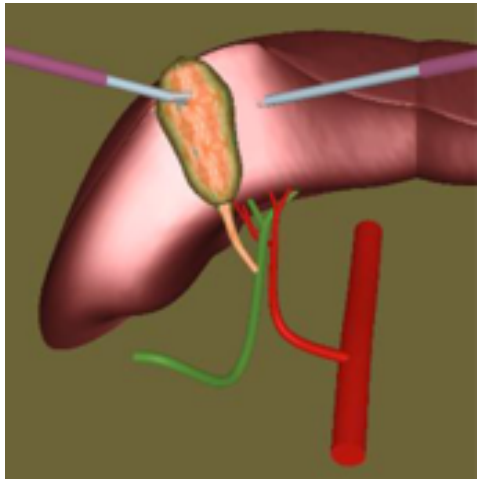
- The movements of the operator are scaled down by the mechanism so that very fine operations can be performed while maintaining a suitable telepresence effect.

- 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.

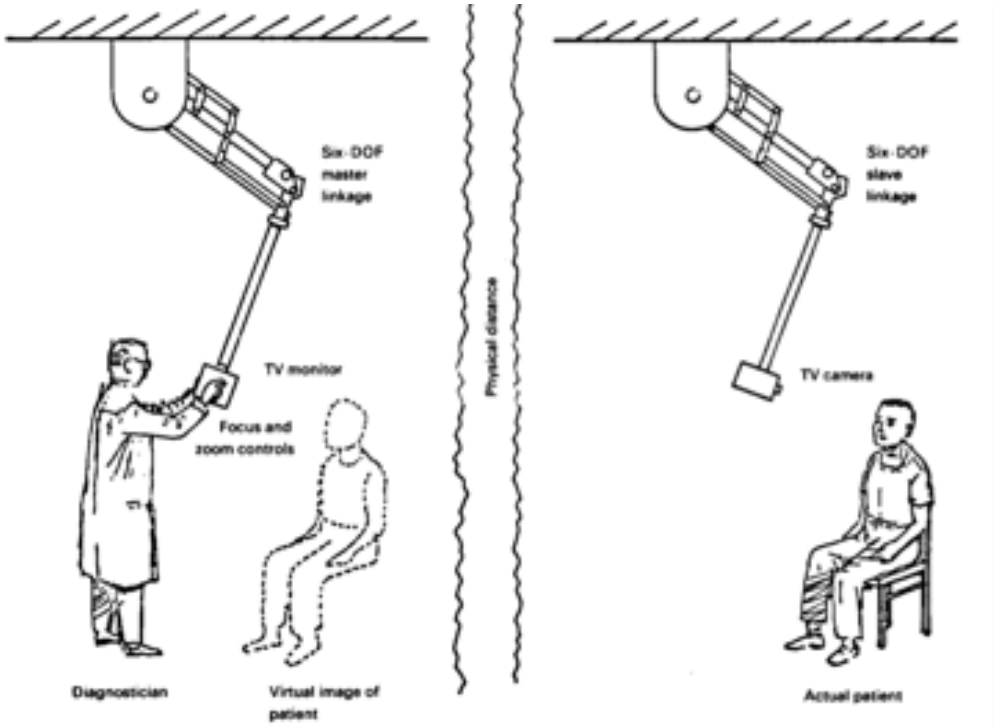
- The increased difficulties for the surgeon are partially compensated by computers, which are used to create virtual environments where the use of telepresence plays a fundamental role.





Telerobotics: Medical applications

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



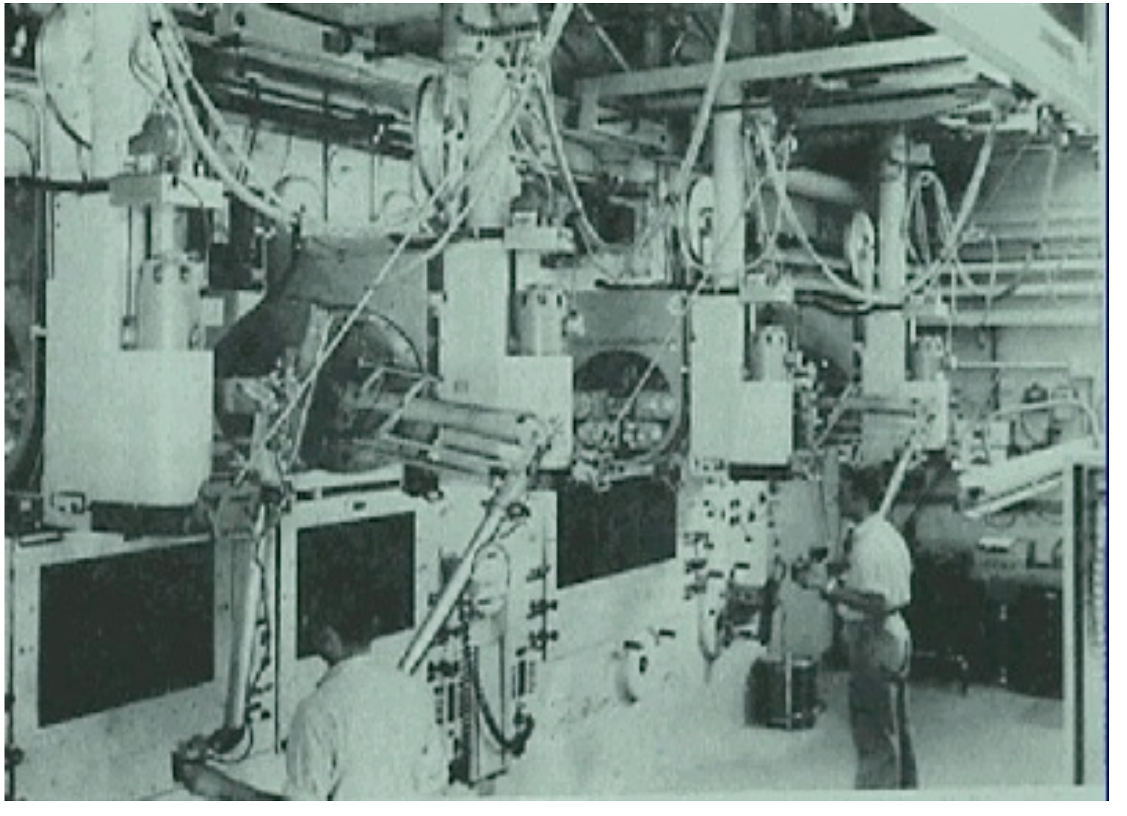
Telemanipulation may be used in surgery operations for:

- 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

Telerobotics: a brief history

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.

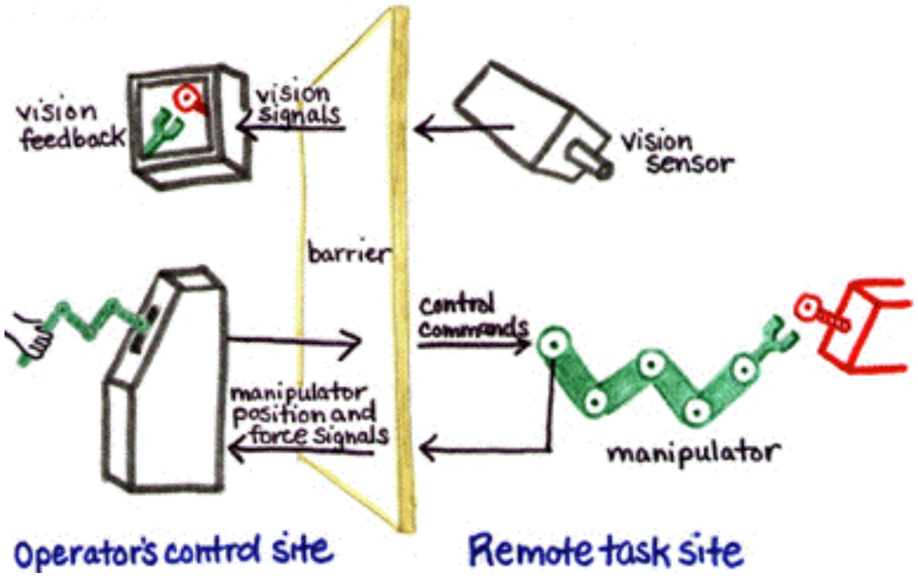


Control Problems

- 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.

- At both sides, energy exchange takes place.



Control Problems

There are some features of this kind of manipulators which are not present in an "usual" robotic system:

- A human operator for the high-level control of the activities;

  Since the operator represents the main "controller" of the system, he/she needs information about the evolution of the task:

  - 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, ...

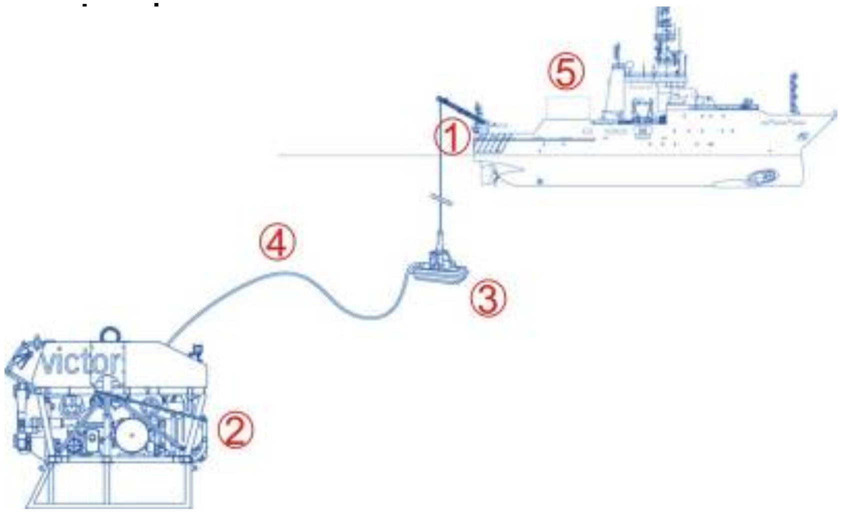
- A communication channel between the master and the slave;

  This channel may represent a source of problems when a time-delay (or limited bandwidth) 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 tenths of a second may create instability problems.

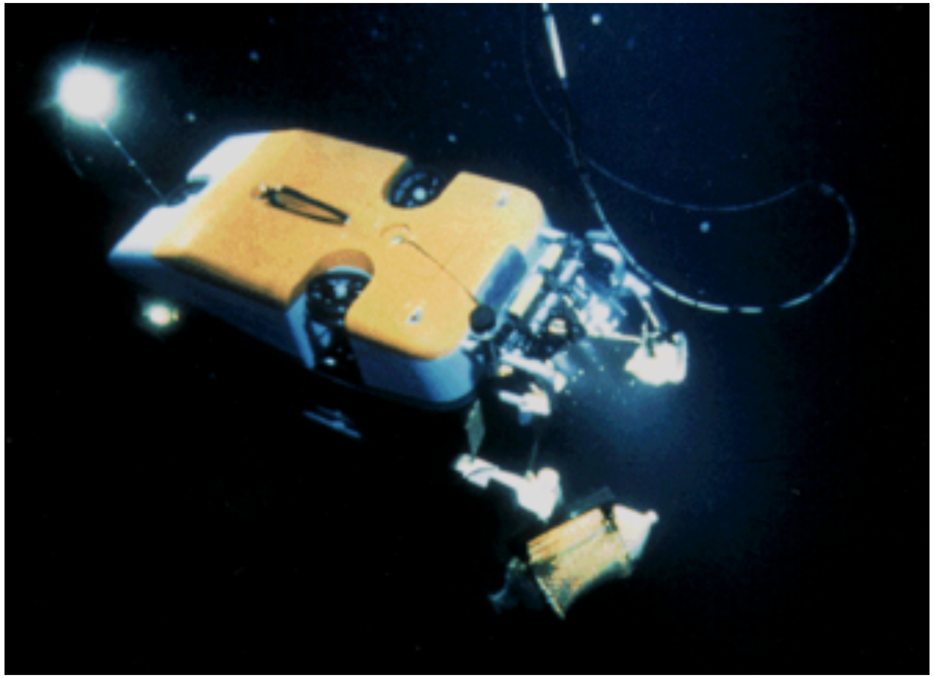
  Transmission of signals (master, slave):

  - choice of suitable signals (position, force, vision, temperature, …);
  - choice and computation of the “coordination”



Control Problems

- An unstructured environment;
  with unknown physical properties (friction, mass, impedance, disturbances…)



Control Problems

- **Two distinct and (possibly) different robotic systems:**
  different kinematics, dimensions, work space, impedance characteristics, dynamic properties, …;

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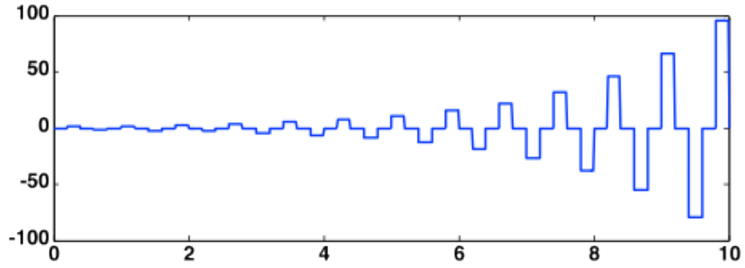
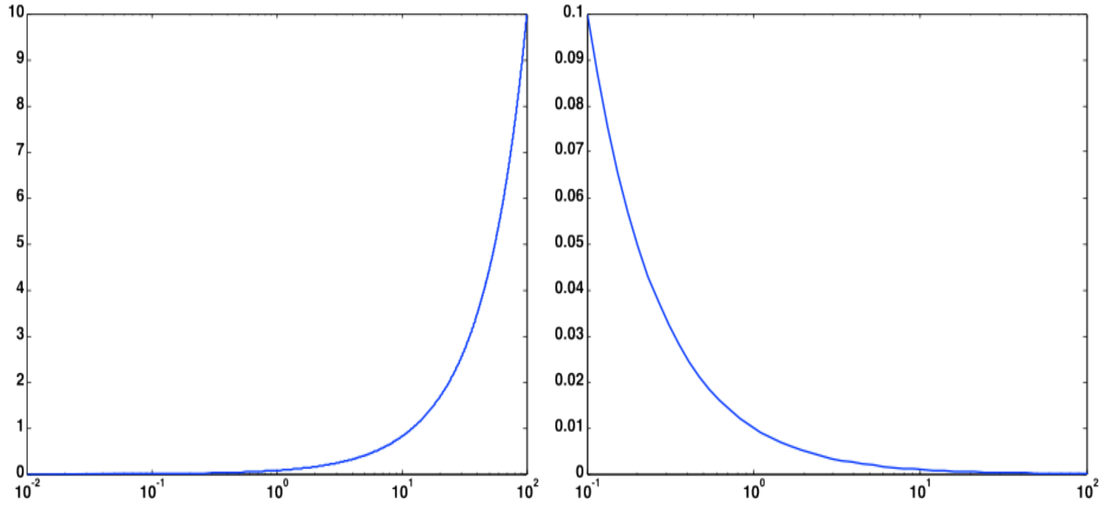
Control Problems - Goals

Possible goals of the overall control systems:

- Stability
- Performance



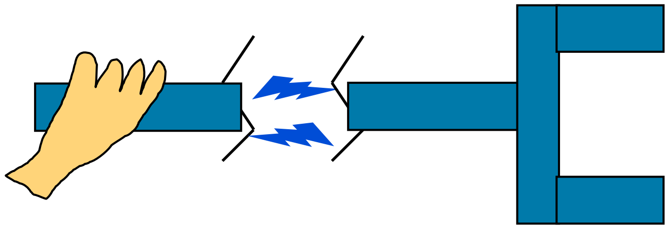
Aspects often in conflict!



Control Problems - Goals

Possible goals of the overall control systems:

- Stability
- Performance
- Telepresence



The goal is to have, in steady state, the slave velocity and force equal to the master's ones, i.e.

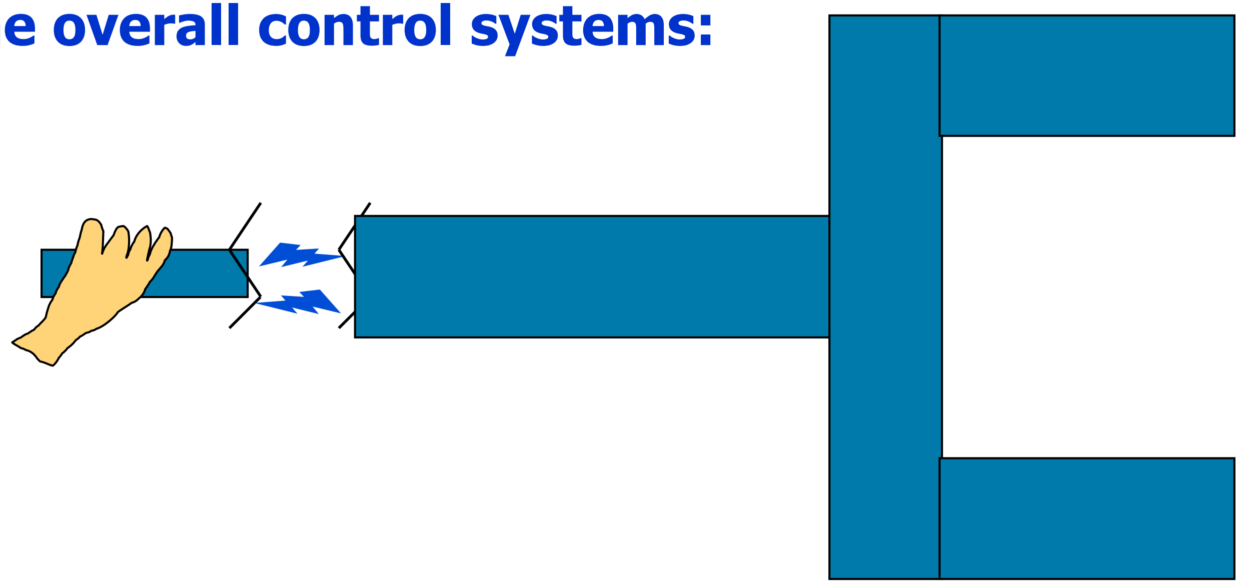
$$\dot{x}_s = \dot{x}_m$$
$$f_m = f_s$$

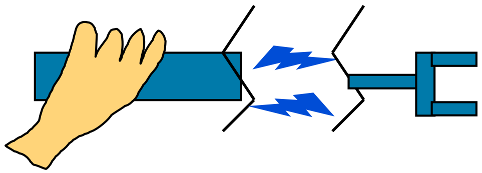
In this case, the teleoperator is defined transparent.

Control Problems - Goals

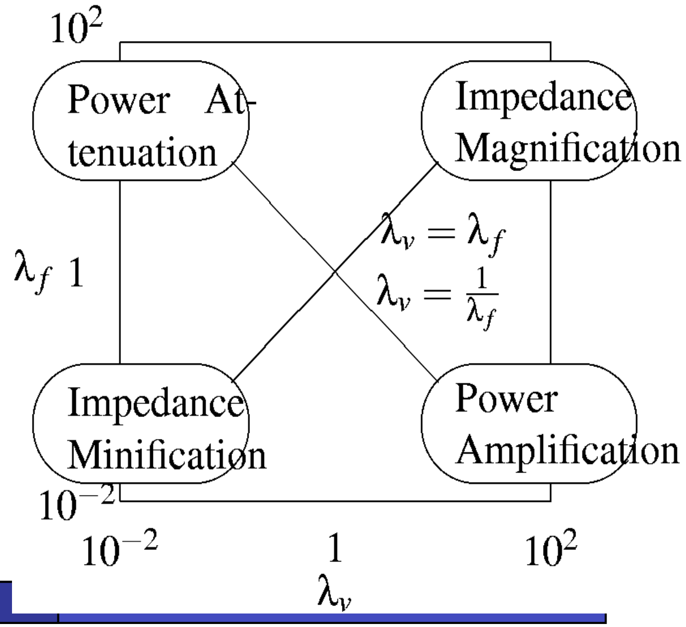
Possible goals of the overall control systems:

- Stability
- Performance
- Telepresence
- Telefunctioning:
  - Power scaling
  - Impedance scaling
  - Impedance shaping





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

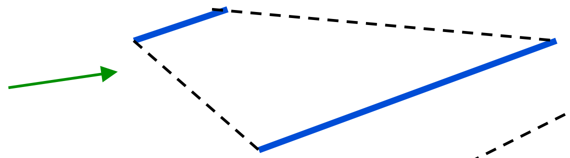


Control Problems: Goals

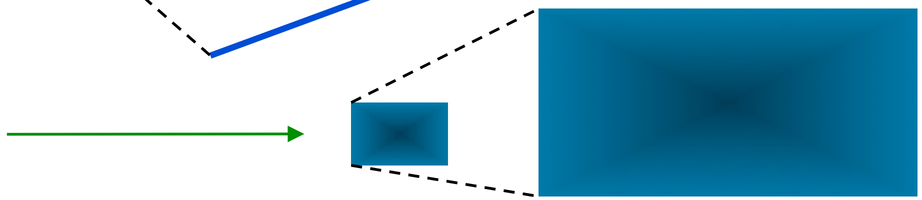
- Scaling physical characteristics: for example a microteleoperation system is intended to scale up the environment by a factor of K.

- We can set appropriate scaling factors λ_f and λ_v to have a correct kinesthetic perception **BUT**

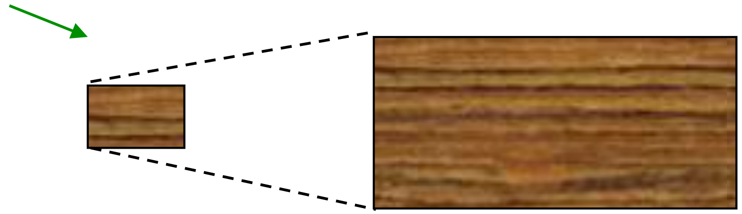
  - Visual size is scaled by K



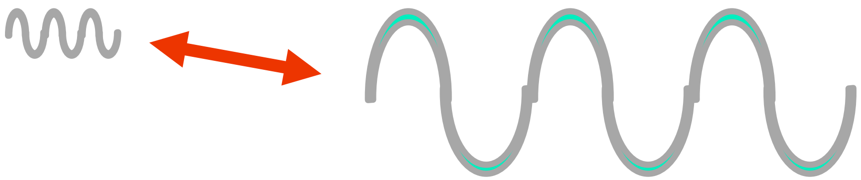
  - Surface area is scaled by K^2



  - Mass is scaled by K^3



  - Natural frequency?
  - Non linear friction effects?

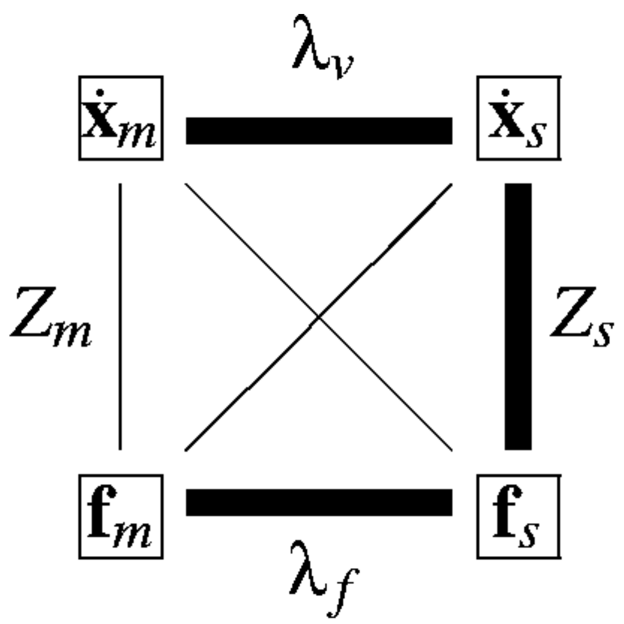


Control Problems: Goals

- Three independent relationships can be assigned between the four variables:

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

- 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.



Control Schemes

- These features have generated a more than relevant quantity of control schemes: one could observe that, in principle, any control methodology (passivity, variable-structure, small-gain, adaptive, H_1, …) has been applied to this challenging field.

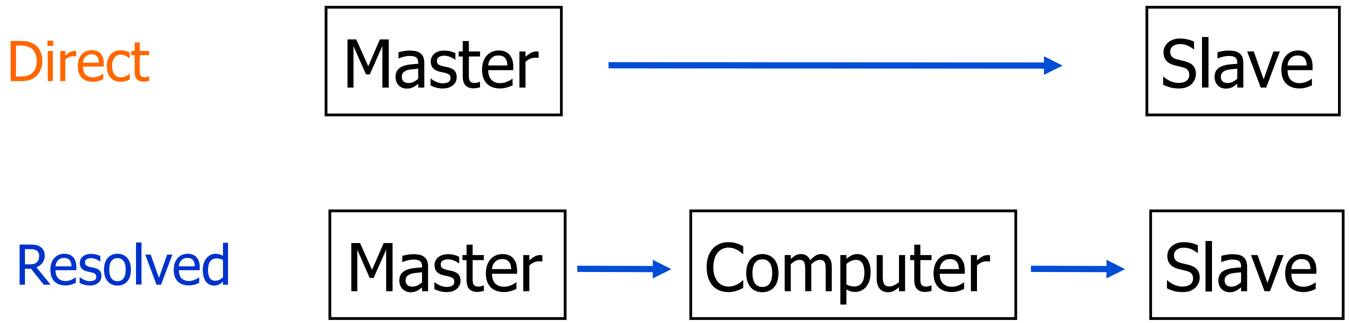
- On the other hand, although the research in this field is very rich, there is not a standard solution or approach, neither it is clear what could be considered “the best” control scheme.

- It could be argued that it is not even clear the definition of a performance criterion by means of which different control schemes can be compared.

Control Schemes – General Remarks

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

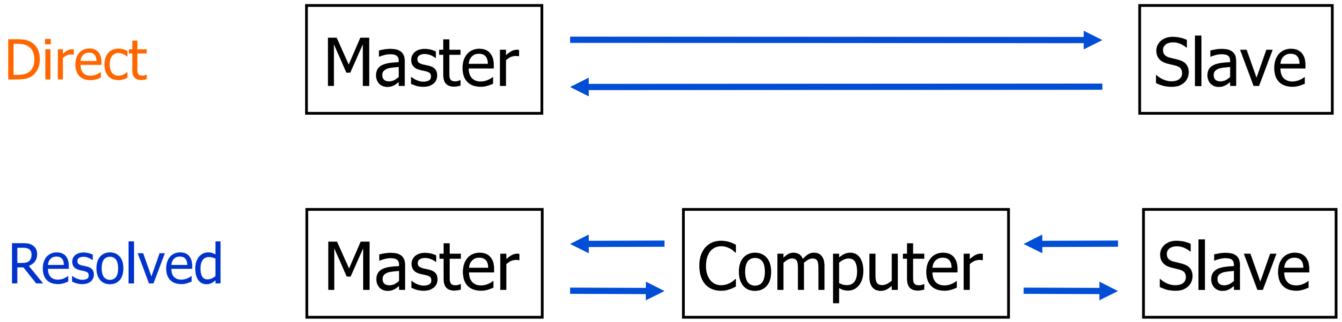
- **Unilateral rate control:**
  - direct
  - resolved
- **Unilateral position control:**
  - direct
  - resolved



Control Schemes – General Remarks

Bilateral rate control:

- direct
- resolved

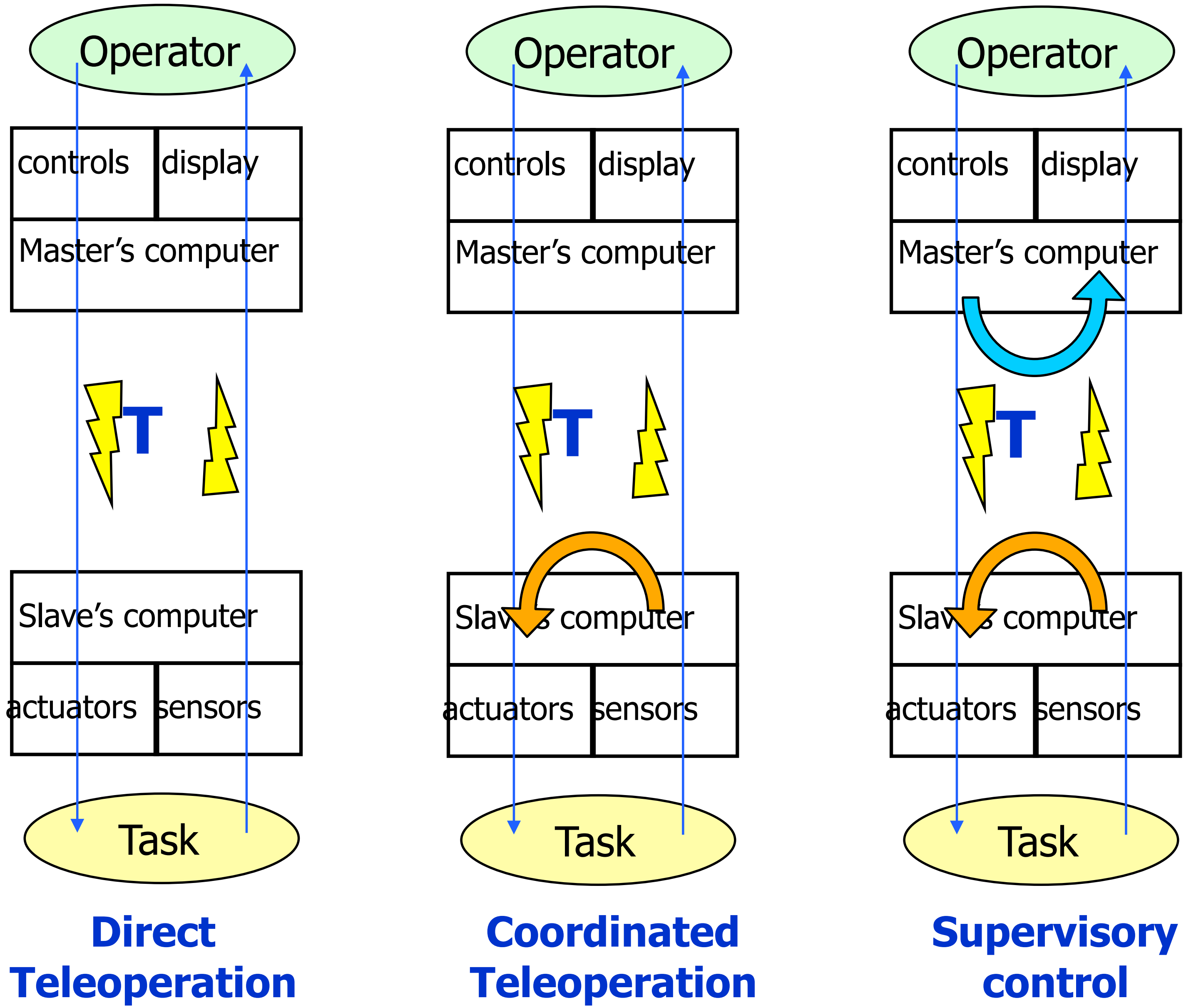


Operator aiding control:

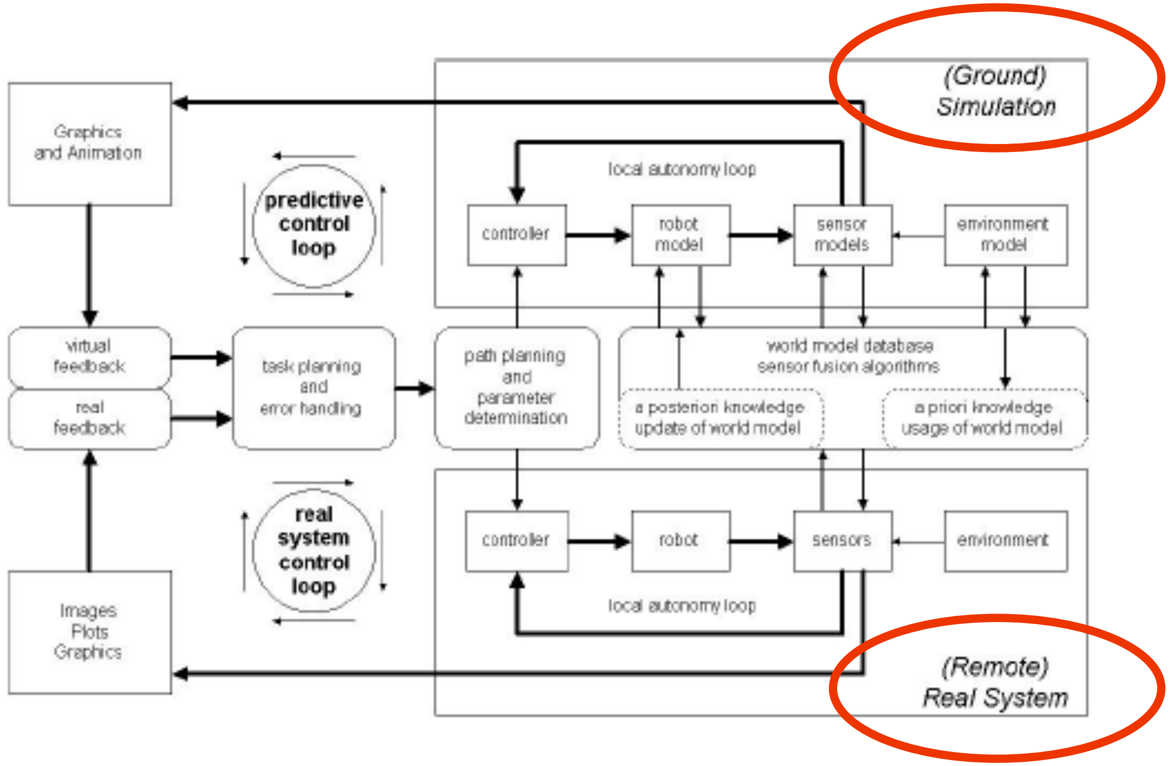
- Filtering
- Scaling
- Referencing
- Motion constraints or compensation
- Simulation

Control Schemes – General Remarks

Bilateral Control Schemes



Concept of Tele-Sensor-Programming (DLR – Rockviss)



Control Schemes – General remarks

- Presence of Time delay
- Interaction with environments
- Unstructured objects/environments
- Nonlinear dynamics

Moreover:

- Forces/velocities often chosen as transmitted signals (impedance/admittance envs.)
- “Port” concepts (interconnection of sub-systems)

Passivity-based controllers
have been successfully adopted

Control Schemes – General remarks

Reasons for passivity-based controllers:

- Elegant and powerful tool for analyzing complex systems
- Composition of passive systems results in a passive system
- Time delay related to transmission does not affect stability
- Linear/non linear dynamics

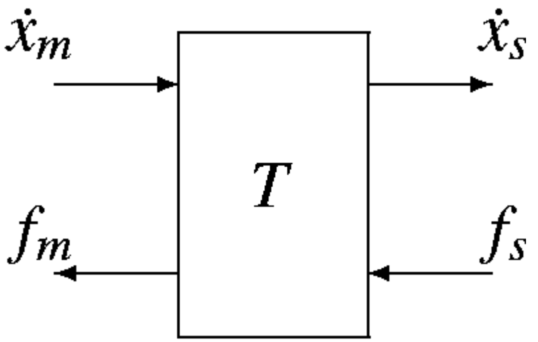
Passivity-based controllers alone do not guarantee stability:

- **The communication channel must be properly considered**

Scattering (waves) variables are often used to transmit information along the communication channel

Paynter, 1960
Ramo,Whynnery, van Duzer, 1965

Transmission of power variables

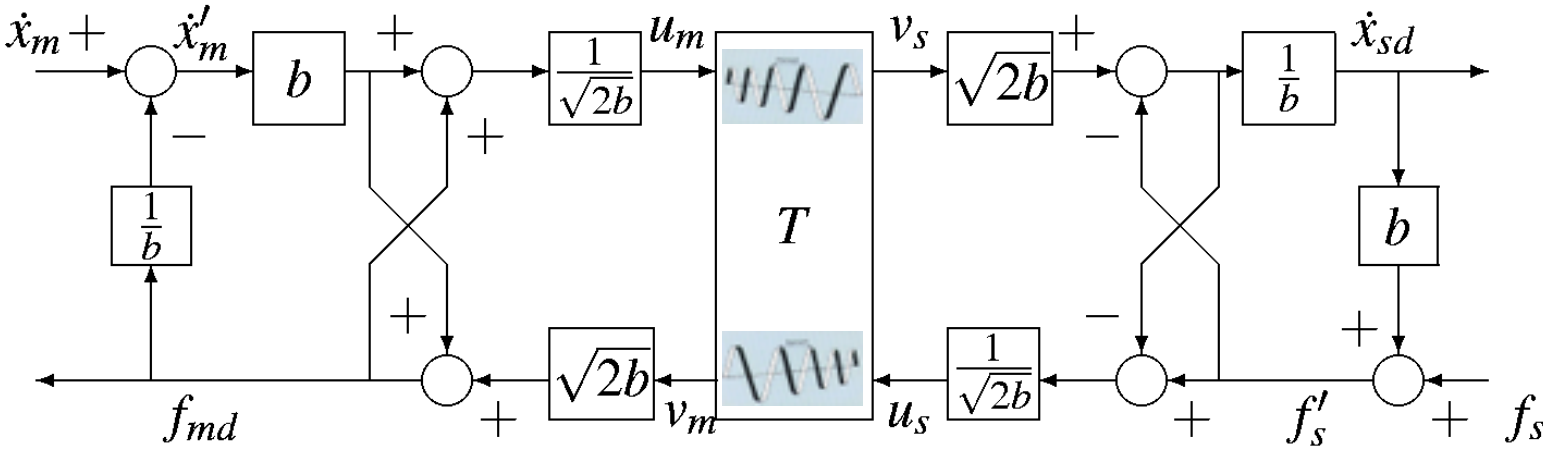


$$\begin{cases} f_m(t) = f_s(t-T) \\ \dot{x}_s(t) = \dot{x}_m(t-T) \end{cases}$$

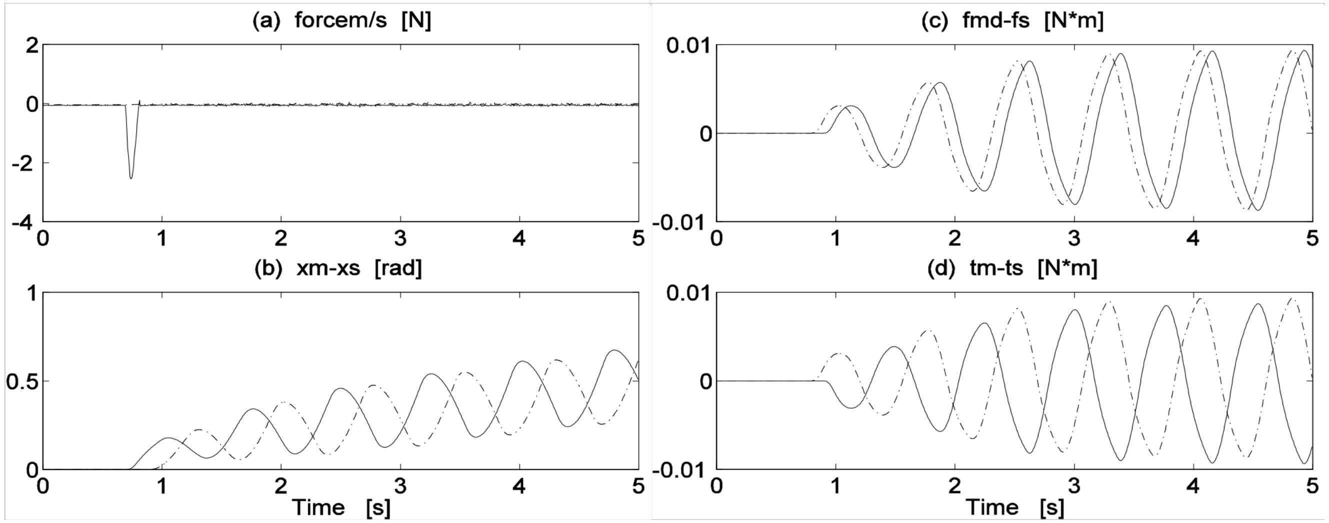
R.J. Anderson, M. Spong, IEEE TRA, 1989
G. Niemeyer, J.E. Slotine, J. Oceanic. Eng., 1991

Transmission of scattering variables

$$v_s(t) = u_m(t-T)\ , \qquad v_m(t) = u_s(t-T)$$



Transmission of power variables



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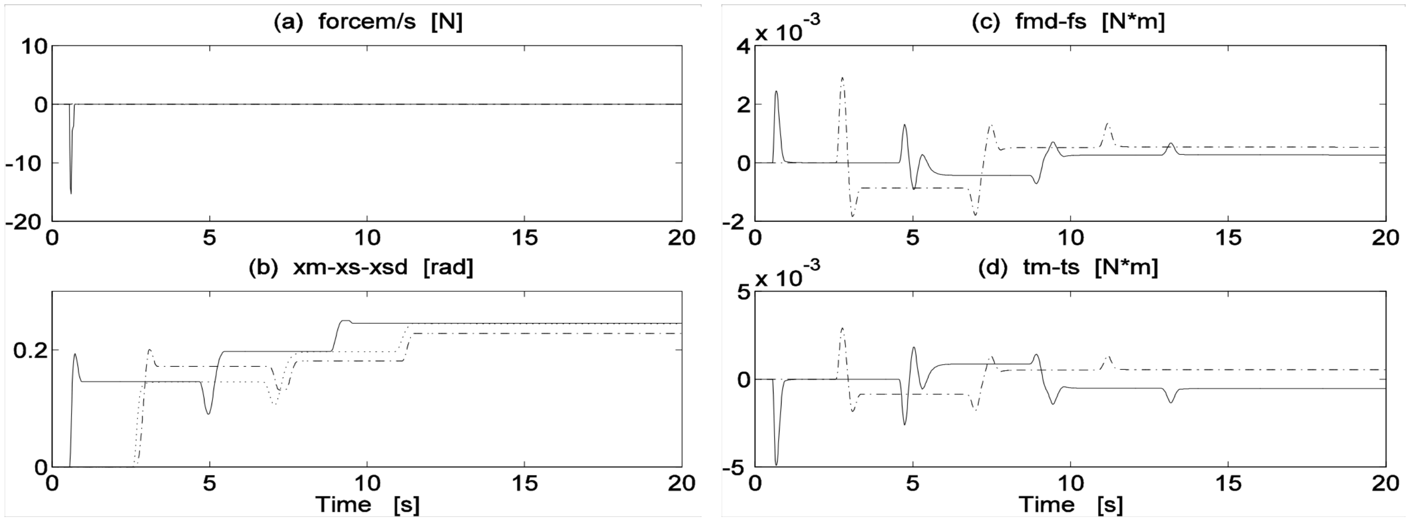
Transmission of scattering variables



Robotica Industriale LM

Robotic Telemanipulation: Modelling and Control Aspects
End – Part 1

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