Università di Roma "La Sapienza"

Medical Robotics

Control Modalities

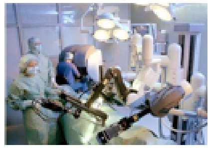
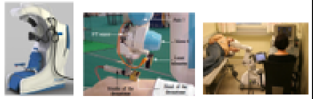
Teleoperated Systems

So how to control a system from a remote site.

Marilena Vendittelli

April 24, 2020

teleoperated systems

domain of use	function	control modality	kinematic architecture	sensors and actuators
orthopedics 	machining of rigid surface	autonomous cooperative or "hands-on"		
MIS 	constrained manipulation	teleoperation shared control	teleoperation allows us to enter with hand inside the human body throught very small insitions without opening it. So the motion and the gesture of the surgeon are transmitted inside the body by means of remote command and control with respect to the surgical tool..	
neurosurgery, interventional radiology, radiotherapy 	constrained targeting	semi-autonomous teleoperation autonomous		
microsurgery 	micromanipulation	shared/cooperative teleoperation		
tele-echography, TMS, skin harvesting 	surface tracking	autonomous teleoperation	when we need to be there but he operator is not necessary an expert	

TELE is the prefix that we can use to indicate an operation that is performed at distance(for ex. the most famous device is the television)

terminology

teleoperation extension of a person's sensing and manipulating capability to a remote location (includes sensors, actuators, communication channel to/from operator)

telepresence operator feels to be physically present at remote site; dexterity of remote device matches that of the bare-hand human operator

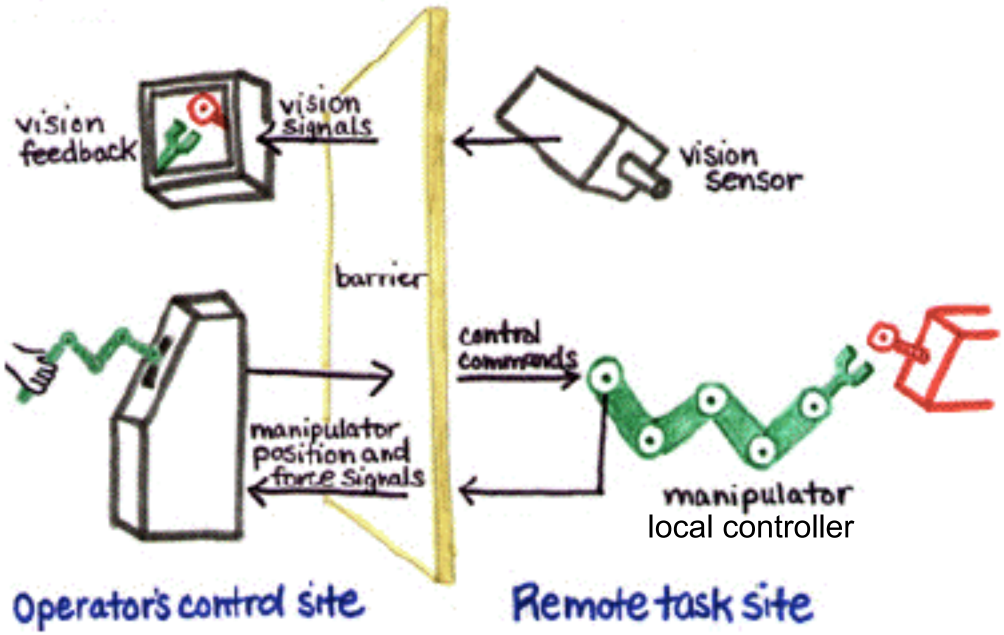
telerobotics remote control of robots; a combination of teleoperation and telepresence

main components

a telemanipulator is a complex electro-mechanical system usually encompassing

- a **master** (or local) device with relative controller
- a **slave** (or remote) device with relative controller
- a **communication channel** between master and slave

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

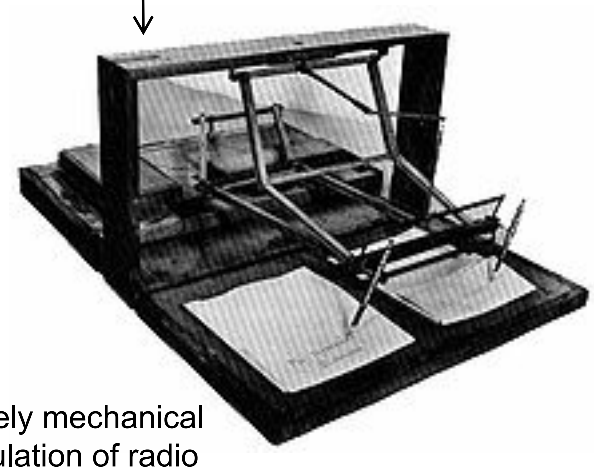


they are connected by a comunication channel between master and slave

2 sites

a brief history

the transmission of the motion is purely mechanical and it is based on the idea of a pantograph which is a linkage parallel mechanism for reproducing the motion that is performed on one side to a remote side



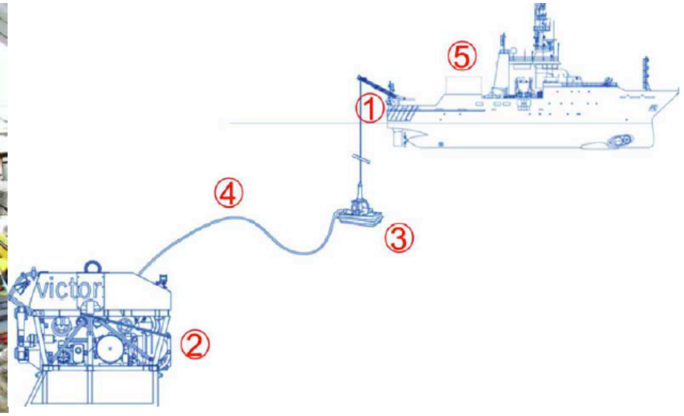
- early 1800, the third american President Thomas Jefferson used (less probably invented) the *polygraph* ~~to~~ produce multiple copies of a letter
- based on a pantograph, a four-bar linkage reproducing the motion on one side to a remote side

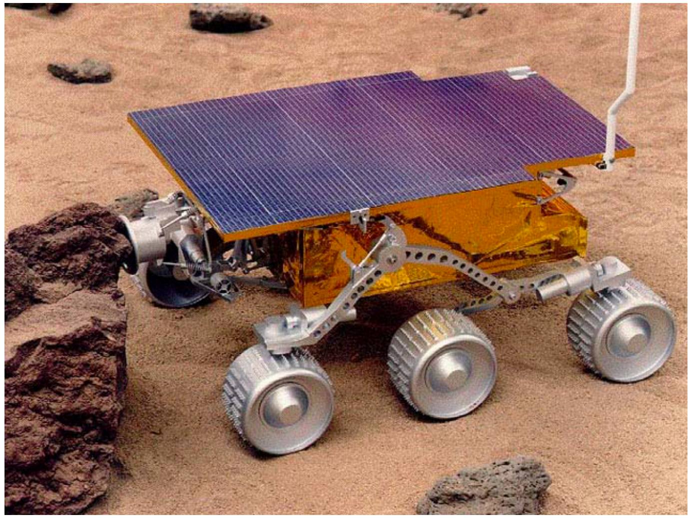
operator that is purely mechanical used for the manipulation of radio active meterial

- mechanical pantographs were developed by Raymond Goertz while working for the US Atomic energy Commission at Argonne National Laboratory (where Enrico Fermi developed the first nuclear reactor) and used for handling radioactive materials (1940s)
- 1954: electromechanical manipulators with feedback servo control
- 1960s: closed circuit television and head-mounted displays

applications

submarines, space, military, medical . . .





peculiarities of telemanipulators

- presence of a **human operator** for high-level control

  it requires, first of all the feedback from the slave to the master, so info about the forces exchanged at remote side, about position of the slave manipulator, so visual data but also tactile or acoustic info

  - a feedback from slave to master is necessary (information on exchanged forces, position of the slave, video data, tactile or acoustic information)
  - suitable user interface

- presence of a **communication channel** between master and slave, potential source of problems due to delays or limited bandwidth
  - choice of the signal to be transmitted (position, force, vision, temperature, . . .)
  - choice and computation of the "coordination signal"

    if there isn't coordination between 2 delayes there can be instability.

both systems are manipulators with elechtromechanical system, not only mechanical,

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

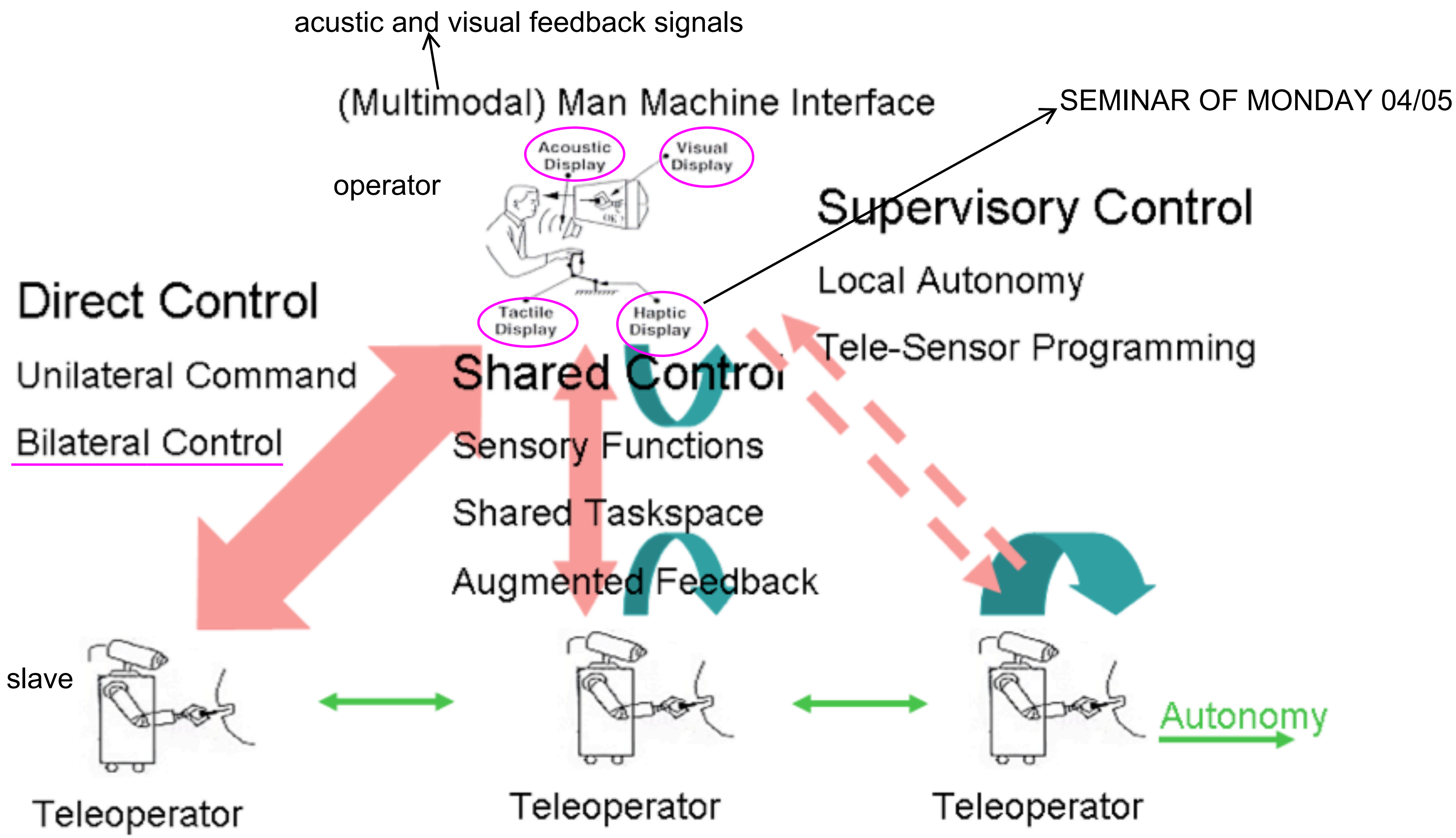
  the DaVinci is the perfect ex

- **unstructured environment** with unknown physical properties (friction, mass, impedance, disturbances. . .)

we can choose which signal to be exchange. This is what we can do in teleoperation

depending on the type of connection between master and slave, control architectures can be organized in three main categories

- direct control
- shared control
- supervisory control



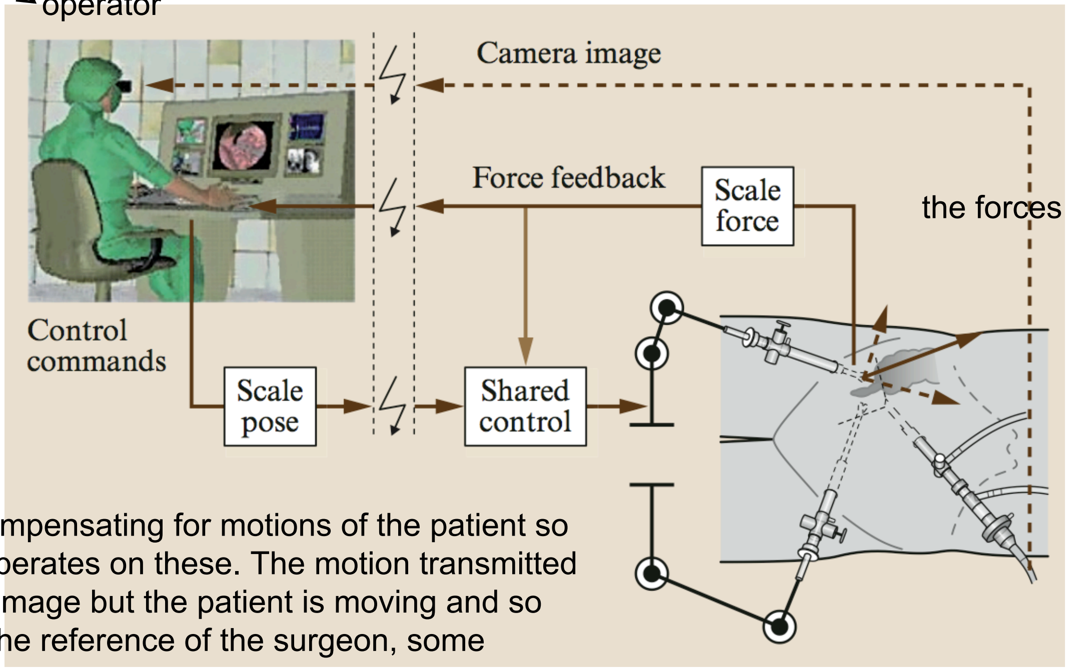
shared control

- local sensory feedback loops at the teleoperator site allow to refine autonomously gross commands by human operator providing the teleoperator with a modest kind of sensory intelligence
- in applications with large time delays the shared autonomy concept distributes intelligence between the operator and the teleoperator during task execution

it sends control command and receives the feedback of for ex. visual type(from endoscope camera system) and force feedback

example

operator



the forces exchanged could be very small

the camera images are stabilized by compensating for motions of the patient so the surgeon will see static imags and operates on these. The motion transmitted to the slave will be related to the static image but the patient is moving and so locally, the loccal controller will add to the reference of the surgeon, some motions to compensate the patient.

the autonomous part of the system controls and compensates the patients movements while the surgeon controls the operation itself on a virtual stabilized patient

- position control and kinematic coupling
  - the two manipulators could be kinematically different and the initial position (properly transformed) could not be the same: they must be connected or the offset should be considered in the control

    we can reset the offset or we need to take into account the offset
  - once connected, the manipulators might be temporarily disconnected, for example to reposition the master (*clutching*) master and slave don't need to be connected all the time
  - if the mechanisms are equivalent or kinematically identical they can be connected at the joint level

    for ex. the size are different but have the same dof

$$\boldsymbol{q}_{sr} = \boldsymbol{q}_m + \boldsymbol{q}_{\text{offset}} \qquad \boldsymbol{q}_{mr} = \boldsymbol{q}_s - \boldsymbol{q}_{\text{offset}} \qquad \boldsymbol{q}_{\text{offset}} = \boldsymbol{q}_s^0 - \boldsymbol{q}_m^0$$

    with m: master; s: slave, r: reference (desired value)

    sr:slave robot
  - kinematically dissimilar robots are connected at their tips

    positions: $\boldsymbol{x}_{sr} = \boldsymbol{x}_m + \boldsymbol{x}_{\text{offset}} \qquad \boldsymbol{x}_{mr} = \boldsymbol{x}_s - \boldsymbol{x}_{\text{offset}}$

    orientation of the master/slave with respect frame 0

    orientations: $\boldsymbol{R}_{sr} = \boldsymbol{R}_m \boldsymbol{R}_{\text{offset}} \qquad \boldsymbol{R}_{mr} = \boldsymbol{R}_s \boldsymbol{R}_{\text{offset}}^T \qquad \boldsymbol{R}_{\text{offset}} = \boldsymbol{R}_{m,0}^T \boldsymbol{R}_{s,0}$ ${}^0R_M \quad {}^0R_S$

    if a video camera and a monitor are used at the remote and local site respectively, to make the connection appear natural, position and orientation of the slave should be measured relative to the camera while master position and orientation should be measured relative to the user's view

– different sizes of the manipulators require scaling of physical characteristics

$$\boxed{\begin{aligned} \dot{x}_s &= \lambda_v \dot{x}_m \\ f_m &= \lambda_f f_s \\ f_s &= Z_s \dot{x}_s \end{aligned}} \qquad\qquad Z = Ms + b = \frac{f}{\dot{x}}$$

three independent relationships can be assigned between the four variables $\dot{x}_{m/s}$, $f_{m/s}$

* telepresence ($\lambda_v = \lambda_f = 1$) realizes a dynamic similarity between master/slave variables
* appropriate choice of the scaling factors λ_v and λ_f provide a correct kinesthetic perception (sensation of movement or stress in muscles, tendons, and joints)
* different information (visual, kinesthetic, force, . . .) about the environment scale with different factors

in principle, any control methodology can be applied but a standard approach to the solution does not exist and the definition of a performance criterion by means of which different control schemes can be compared is not clear

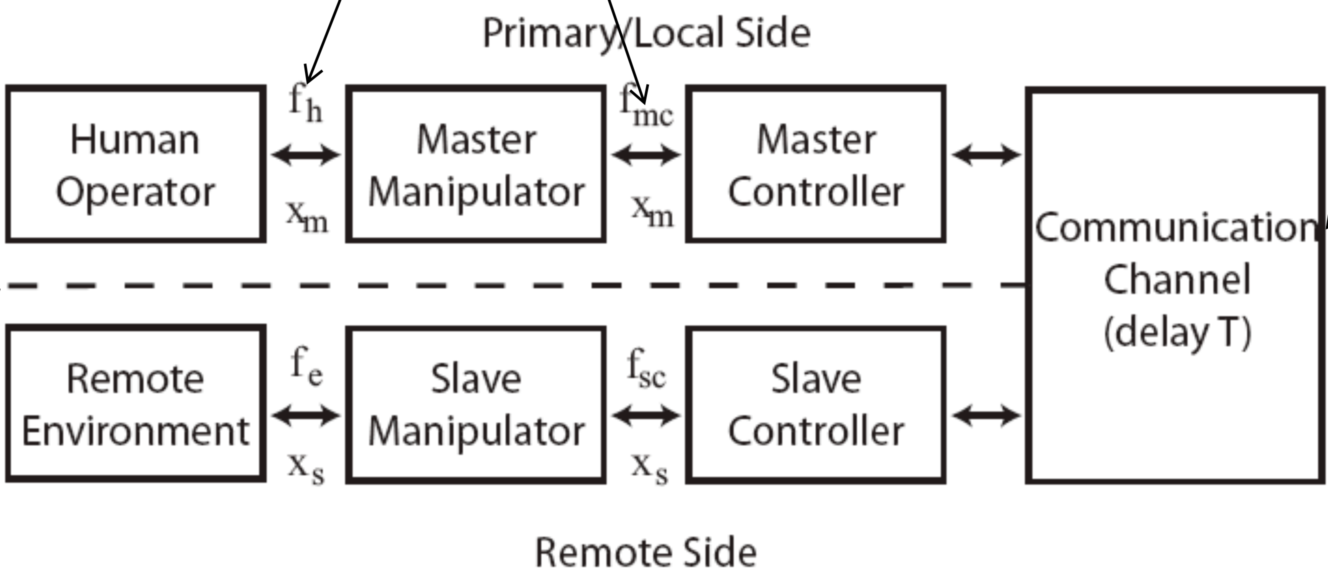
the various control schemes differ in

- the computation of the forces applied to the two manipulators: admittance/impedance relationships for master/slave are possible in various combinations although impedance based schemes are more popular because they do not necessarily require force sensors
- the information exchanged between master and slave
- sensors used in the control scheme
- the computational load
- required bandwidth

the human operator interacts with master manipulator (so it exchanged energy through forces and position)

forces that master controller imposes to master manipulator

these signals that connect one block to the other is a port representation. The port is present where an exchange of energy takes place



it presents some delay

division between primary or master side and remote or slave side

objectives

primary objective

if we apply a force which is bounded then the value of the state must remain bounded.

- **stability**: bounded value of the state (i.e., positions, velocities, internal variables of the local controllers) in response to bounded external inputs (i.e., forces/torques applied by the operator and the environment); delays in communication and controller parameters determine stability properties

in the next lecture we define it mathematically

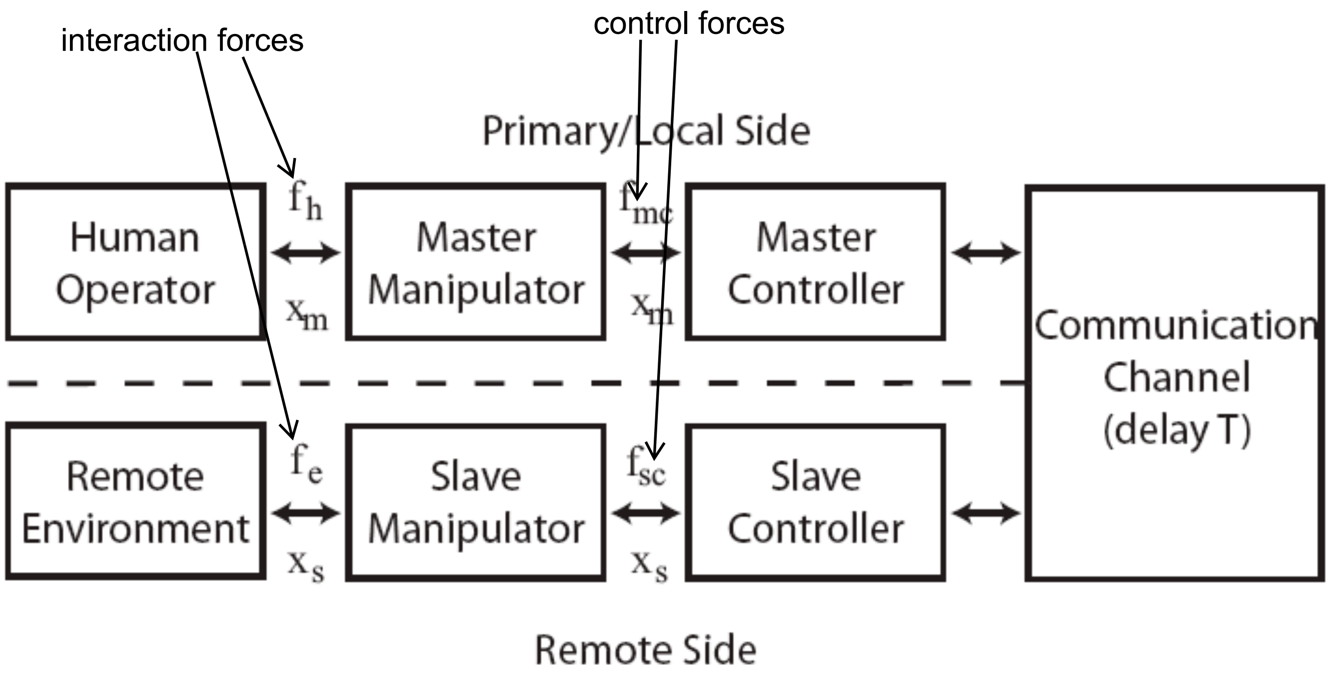
- **transparency**: the operator should perceive a direct physical interaction with the remote environment during task execution

  trasparency is characterized by at least these 4 properties

  - inertia and damping perceived at the master side by the human operator when no force is exerted on the slave manipulator should be low
  - tracking: at the slave side the master manipulator displacements during movements without interaction should be accurate and "fast"; delays could affect performance
  - stiffness perceived at the master by the operator in case of interaction with a structured environment at the slave should be as the one perceived in the interaction at the slave side
  - drift of position between master and slave in case of interaction at the slave side should be zero

we will see 2 simple control schemes, how to generate the control force at the master and at the slave

bilateral control components



$f_{h/e}$ interaction forces with the human/environment; $f_{mc/sc}$ control force first control scheme

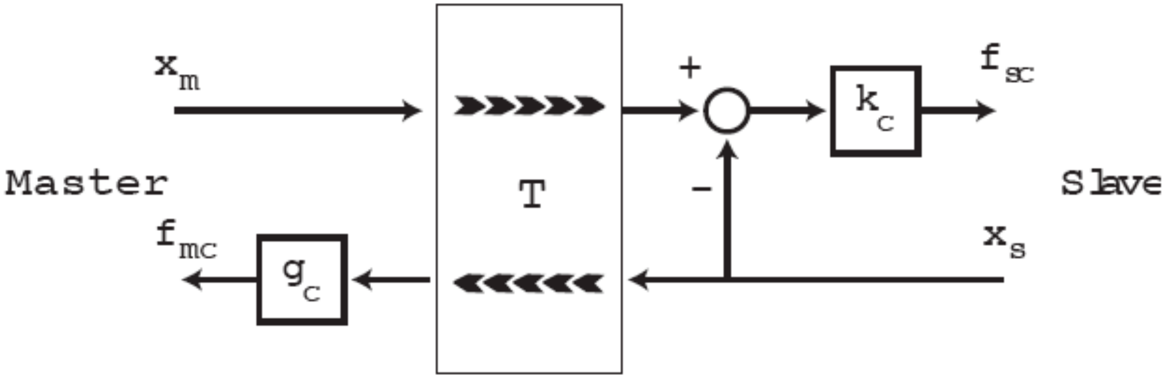
force reflection

$$\begin{cases} f_{mc} & = & g_c f_{sd} \\ f_{sc} & = & k_c(x_{md} - x_s) \end{cases}$$

it sais that it applies a force to the slave which is proportional to the difference between the current master position and the current slave

$$x_{md} = e^{-sT} x_m, \qquad f_{sd} = e^{-sT} f_{sc}$$

is considered also delay in the transmition of the sequence



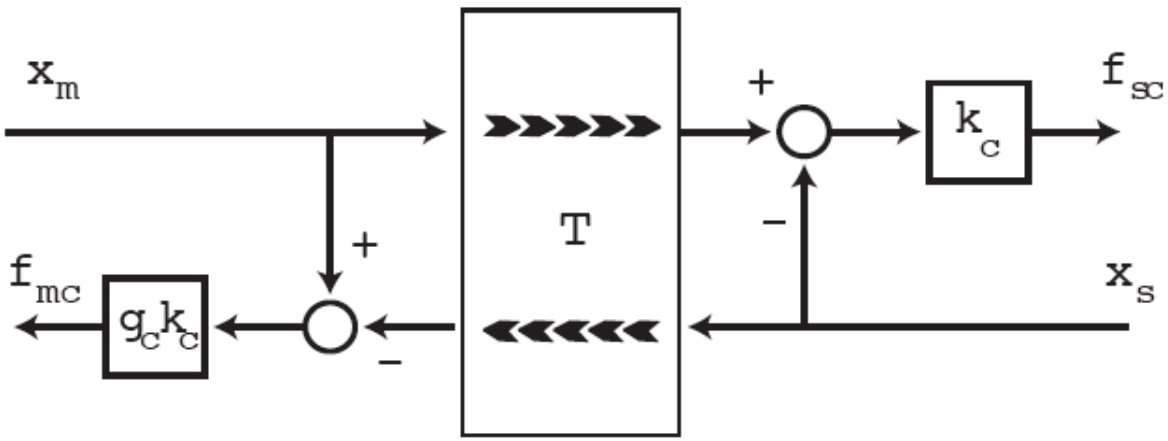
secondo control scheme

position error

error due to the missallignement between 2 positions

$$\begin{cases} f_{mc} & = & g_c k_c (x_m - x_{sd}) \\ f_{sc} & = & k_c (x_{md} - x_s) \end{cases}$$

$$x_{md} = e^{-sT} x_m, \qquad x_{sd} = e^{-sT} x_s$$



properties of SLIDE 13

example

forces applied to the master and the slave

hypothesis: one dof master and slave described by the linear model

$$\boxed{\begin{array}{rcll} (m_m s^2 + b_m s)\, x_m & = & f_m, & f_m = f_{mc} + f_h \\ (m_s s^2 + b_s s)\, x_s & = & f_s, & f_s = f_{sc} - f_e \end{array}}$$

stability

by assuming that the delay is zero the system with appropriate parameters will be stable

both control schemes can be stable with an appropriate choice of the control parameters provided that $T < T_{\max}$

equivalent inertia and damping: perceived at the master side by the human operator when no force is exerted on the slave manipulator

master equivalent inertia and dumping

$$G_1(s) = \left(\left. \frac{x_m}{f_h} \right|_{f_e=0} \right)^{-1} = m_{eq} s^2 + b_{eq} s + G_1^*(s), \qquad \lim_{s\to 0} G_1^*(s)/s^2 = 0$$

force reflection: $\underline{m_{eq} = (1+g_c)m_m - g_c b_m (b_m/k_c + 2T)}$ $\quad \underline{b_{eq} = (1+g_c) b_m}$

position error: $\underline{m_{eq} = 2(m_m - b_m T - k_c T^2) - b_m^2/k_c}$ $\quad \underline{b_{eq} = 2(b_m + k_c T)}$

if T=0 the the gain of the position error has no influence on the perceive duming

tracking: at the slave side of the master manipulator displacements during movements without interaction

master and slave position

const

$$G_2(s) = \left.\frac{x_m - x_s}{f_h}\right|_{f_e=0} = \delta G_2^*(s), \qquad \lim_{s\to 0} G_2^*(s) = 1$$

tracking error

force reflection: $\delta = \dfrac{b_m + k_c T}{b_m k_c (1 + g_c)}$

if T=0 (so tracking error depends on the gain) delta can be made smaller by increasing the gain

position error: $\delta = \dfrac{1}{2 k_c g_c}$

stiffness: perceived at the master by the operator in case of interaction with a structured environment at the slave

const

$$G_3(s) = \left(\left.\frac{x_m}{f_h}\right|_{f_e=-(b_e s + k_e)x_s}\right)^{-1} = k_{eq} G_3^*(s), \qquad \lim_{s\to 0} G_3^*(s) = 1$$

stiffness factor

force reflection: $\boxed{k_{eq} = \dfrac{k_e g_c k_c}{k_e + k_c}}$

we can choose these parameters to making this Keq as close as possible to 1

position error: $k_{eq} = \dfrac{k_e g_c k_c}{k_e + k_c}$

drift: of position between master and slave in case of interaction at the slave side

$$G_4(s) = \left.\frac{x_m - x_s}{f_h}\right|_{f_e=-(b_e s + k_e)x_s} = \Delta G_4^*(s), \qquad \lim_{s\to 0} G_4^*(s) = 1$$

force reflection: $\Delta = \dfrac{1}{g_c k_c}$

position error: $\Delta = \dfrac{1}{g_c k_c}$

Bibliography

"Control schemes for teleoperation with time delay: a comparative study," P. Arcara, C. Melchiorri, Robotics and Autonomous Systems, 38 (2002), pp. 49 –64.

"Experimental Quantitative Comparison of Different Control Architectures for Master–Slave Teleoperation," I. Aliaga, Á. Rubio, and E. Sánchez, IEEE transactions on control systems technology, vol. 12, no. 1, pp. 2–11, 2004.