Medical Robotics

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Stability and Transparency in Bilateral Teleoperation

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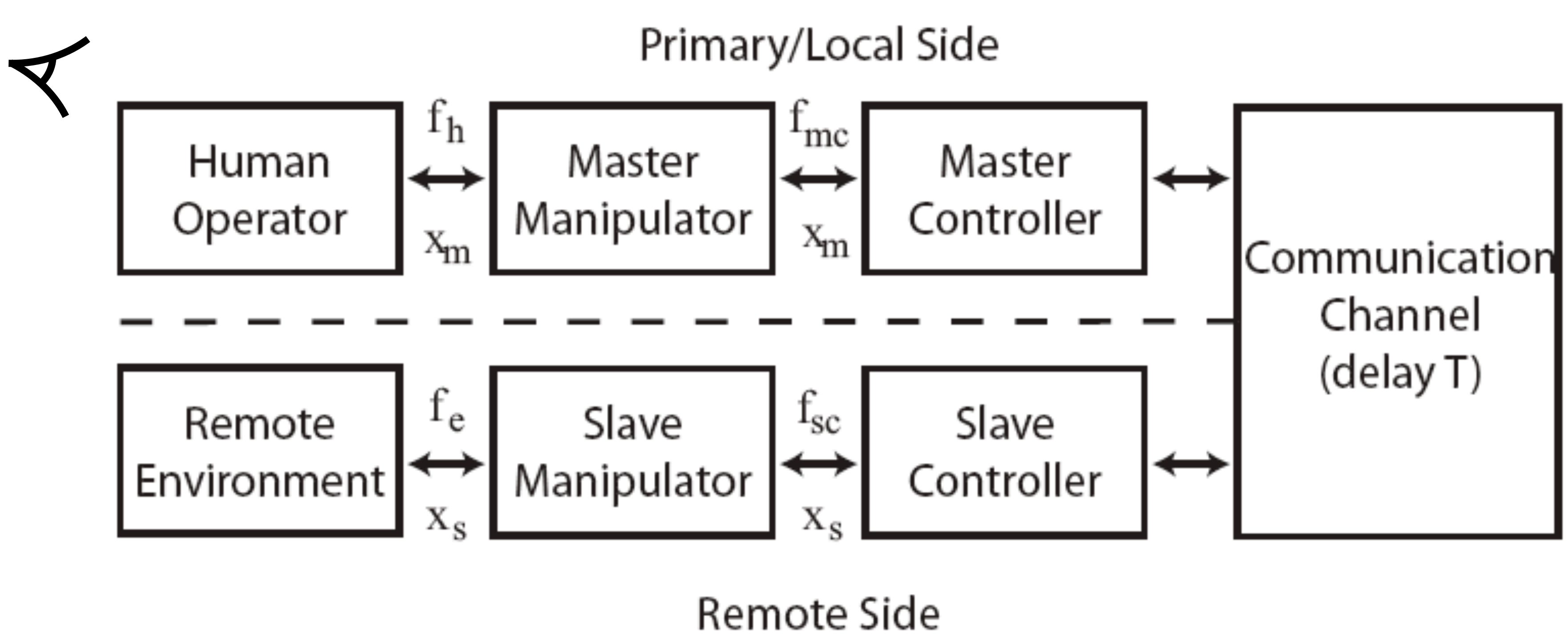
in principle, any control methodology can be applied but a standard approach to the solution does not exist and the definition of a performance criterion by means of which different control schemes can be compared is not clear

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



objectives

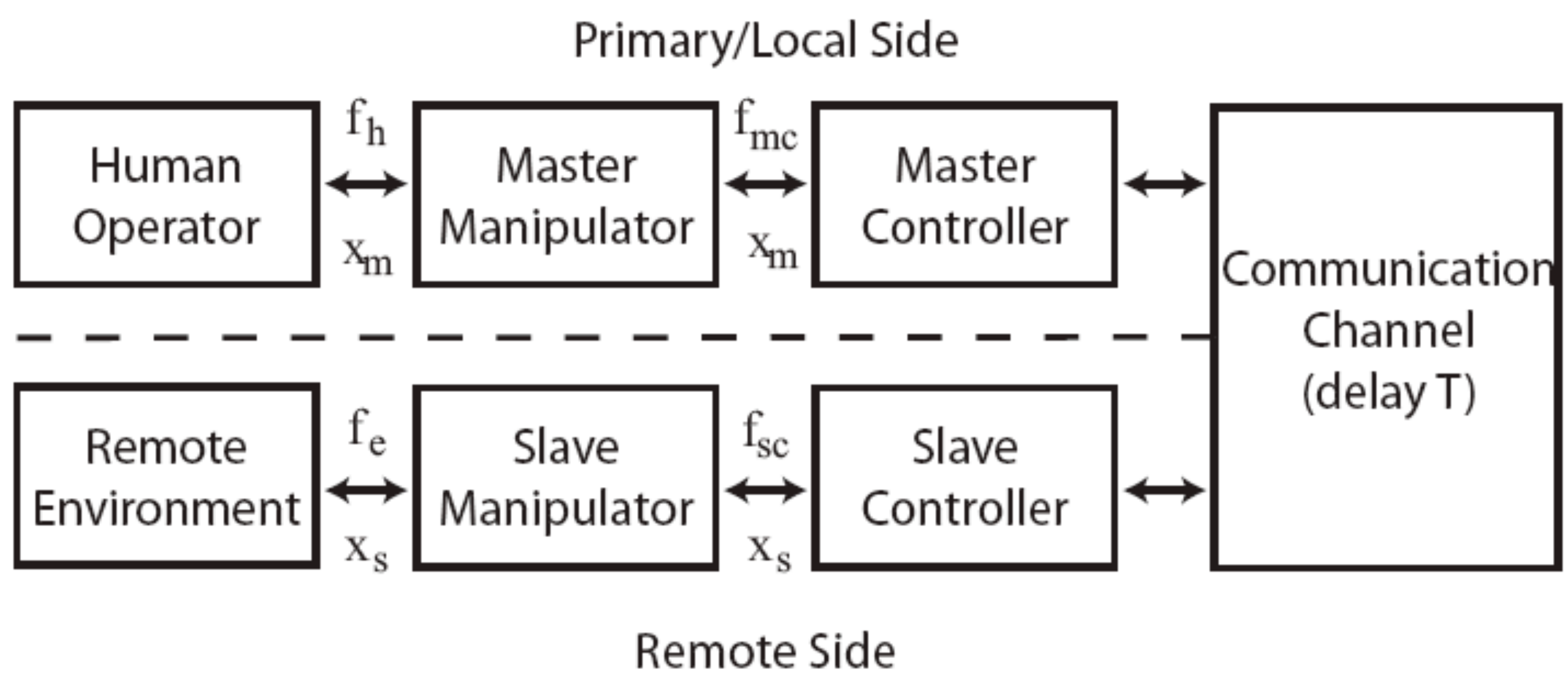
- **stability**: bounded value of the state (i.e., positions, velocities, internal variables of the local controllers) in response to bounded external inputs (i.e., forces/torques applied by the operator and the environment); delays in communication and controller parameters determine stability properties

today we will se a more general methodology

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

The daVinci is a teleoperated system with dedicated communication channel so for which to consider zero delay in the transmission of signal.

bilateral control components



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

all term is a force

between the human operator and remote environment

$$F_h = F_h^* - Z_h \dot{x}_h$$

human-master interaction force

human impedance

if the human is in contact with the master

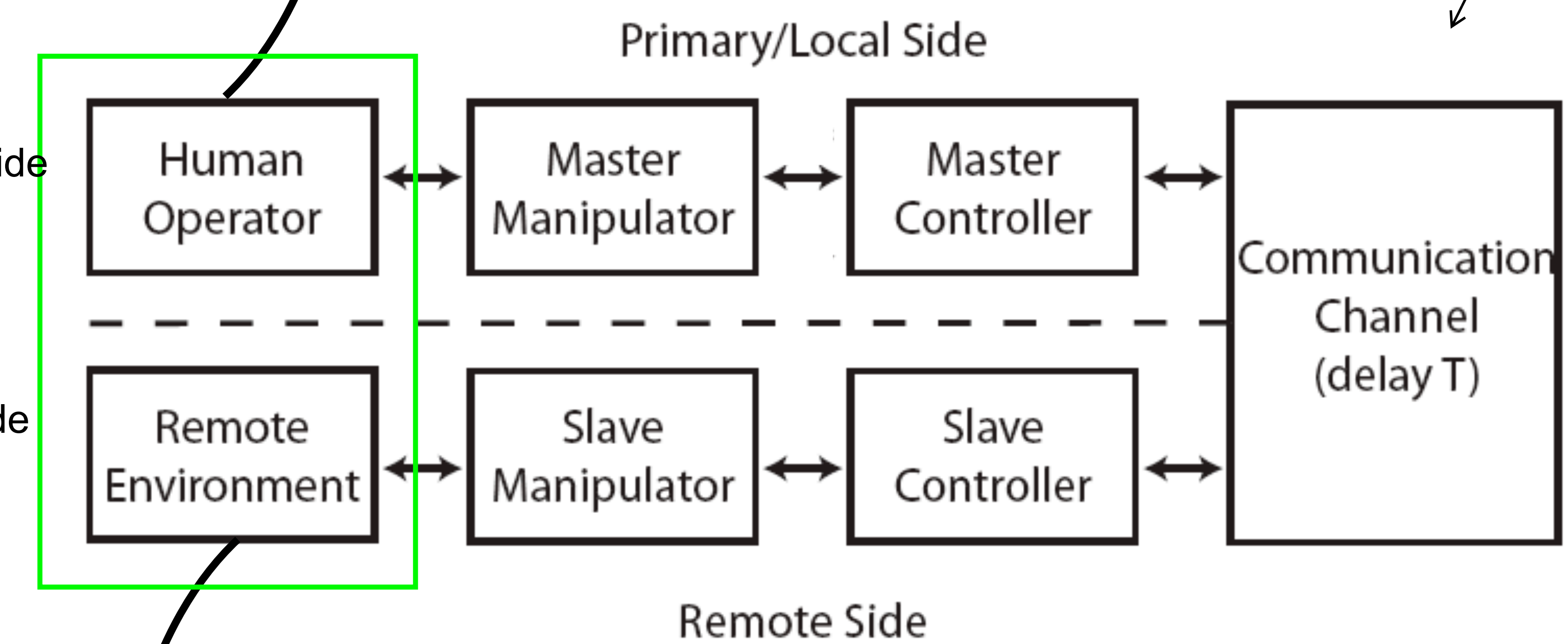
$$M_h \ddot{x}_h + B_h \dot{x}_h + K_h x_h = F_h^* - F_h \qquad x_h = x_m$$

general control architecture

we need a model to analize mathematically this system

master side

slave side



analogous to the master side

$$F_e = \begin{cases} M_e \ddot{x}_e + B_e \dot{x}_e + K_e (x_e - \bar{x}_e) + F_e^* & \text{contact} \quad x_e = x_s \\ 0 & \text{free motion} \end{cases}$$

because there is no contact

interaction force

$$\Downarrow$$

environment reaction force

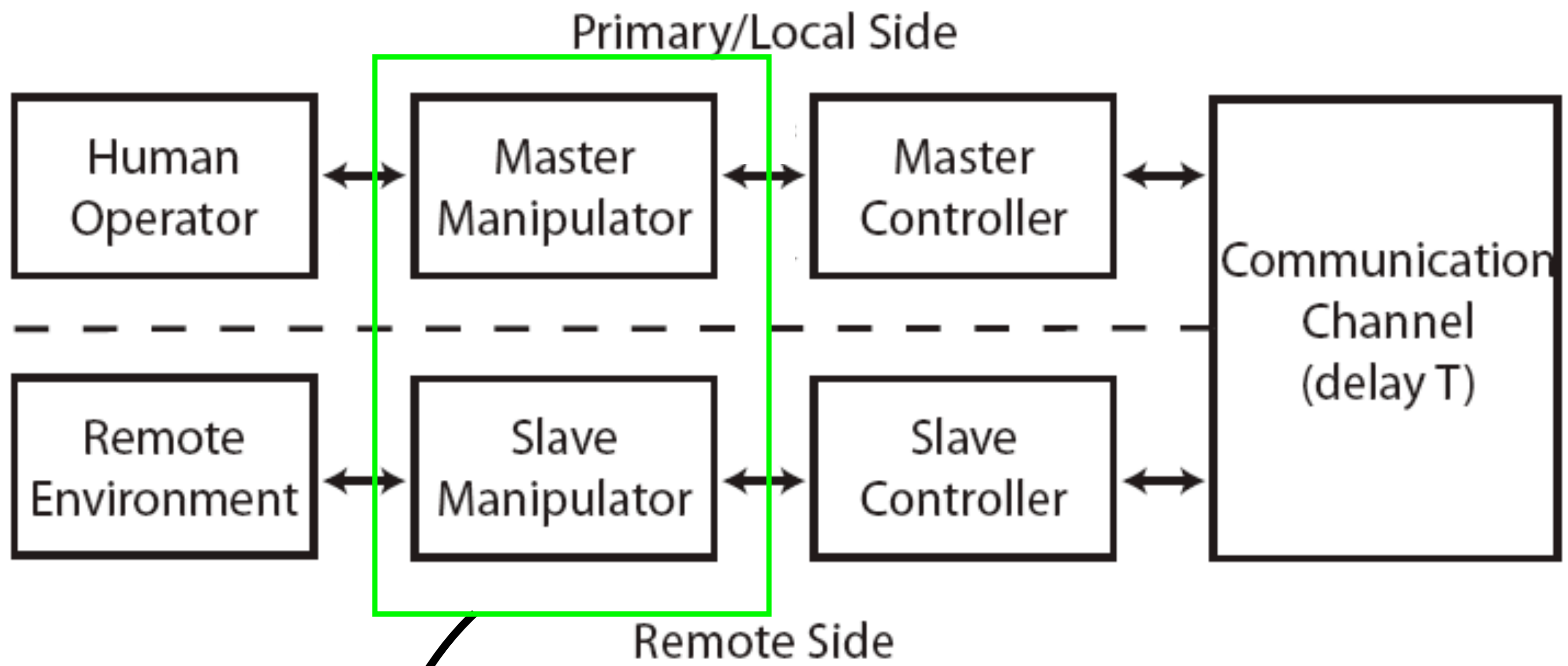
active component of the forces that the environment applies to the slave manipulator

$$F_e = Z_e \dot{x}_e + F_e^*$$

exogenous force (usually considered =0)

usually we assume that the environment is passive

for ex. they are generated from the breathing of the patient….



dynamic model of a manipulator

model written in the joint space

control torque. it's torque generated by the motor at the manipulator joints

$$\begin{cases} M(q)\ddot{q} + C(q,\dot{q}) + F(q,\dot{q}) + G(q) = u & \text{free motion} \\ M(q)\ddot{q} + C(q,\dot{q}) + F(q,\dot{q}) + G(q) = \boxed{u + J^T(q) f} & \text{contact} \end{cases}$$

no contact

external force apply to the manipulator

geometric Jacobian

jacobian at the contact point

in Cartesian coordinates

(necessary to couple kinematically different master and slave)

analogous of external forces applied to the manipulator

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

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

analytic Jacobian

once the manipulator is written in these coordinates(SLIDE 6) we can use the single joint axis approximation which means that we can control in decentralized way each joint then we can operate a feedback linearization in the cartesian space

feedback linearization in Cartesian space

torque

auxiliary input

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

set a dynamic impedance model

inertia force

viscous forces

elastic forces

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

master and slave robot linear single axis approximation

force that the human is applying to the manipulator

for the master manipulator $\longrightarrow$ $M_m\ddot{x}_m + B_m\dot{x}_m + K_m x_m = F_{mc} + F_h$

for the slave manipulator $\longrightarrow$ $M_s\ddot{x}_s + B_s\dot{x}_s + K_s x_s = F_{sc} - F_e$

reaction force of the environment. Force that the manipulator applies on the environment

note: during contact $x_h = x_m$ and $x_e = x_s$

in the frequency domain

EFFORT and FLOW are more general class to which force and velocity are applied, we will see the analogous in the elechtrical system(effort->voltage and flow->current).

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

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

intentional motion

resulting interaction force between the human and the master manipulator

impedance of human

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

in frequency domain X is the position and s the velocity

velocity of human hand that will be the same of the master manimulator if they are in contact

velocity of the master manipulator

admittance

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

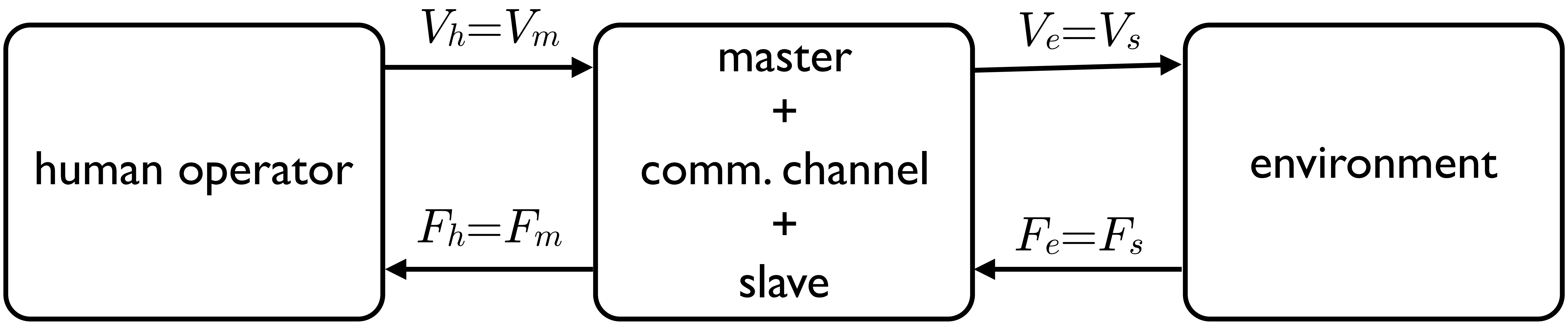
forces applied to the master manipulator(control force: Fmc and interaction force with the human hand:Fh)

Slave robot $$Z_s^{-1}(s) = \frac{sX_s(s)}{F_{sc}(s) - F_e(s)} = \frac{s}{m_s s^2 + b_s s + k_s}$$

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

the system itself with its dinamic communicates with other blocks or with the environment through a port or two ports. A port is where there is an exchanged of energy between 2 blocks.

a two-port model of teleoperator



to quantify the energy exchanged

- **lumped parameter elements**: physical entities who's energy (storage elements) or power (dissipative elements) is defined by a scalar (e.g., mass, resistor)
- **network**: a system described by lumped parameter elements connected in series and parallel (e.g., RLC circuit)
- **port**: a location where energy can move into or out of a network (e.g., contact point between human and haptic interface)

- analysis of energy flow in a network provides key insights

- the derivative of energy is power and can be expressed as the product of two variables: **effort** $\mathcal{E}$ and **flow** $\mathcal{F}$

- effort and flow are linked together by the behavior of systems at their ports through

  - impedance $Z = \mathcal{E}/\mathcal{F}$

  - admittance $A = \mathcal{F}/\mathcal{E} = 1/Z$

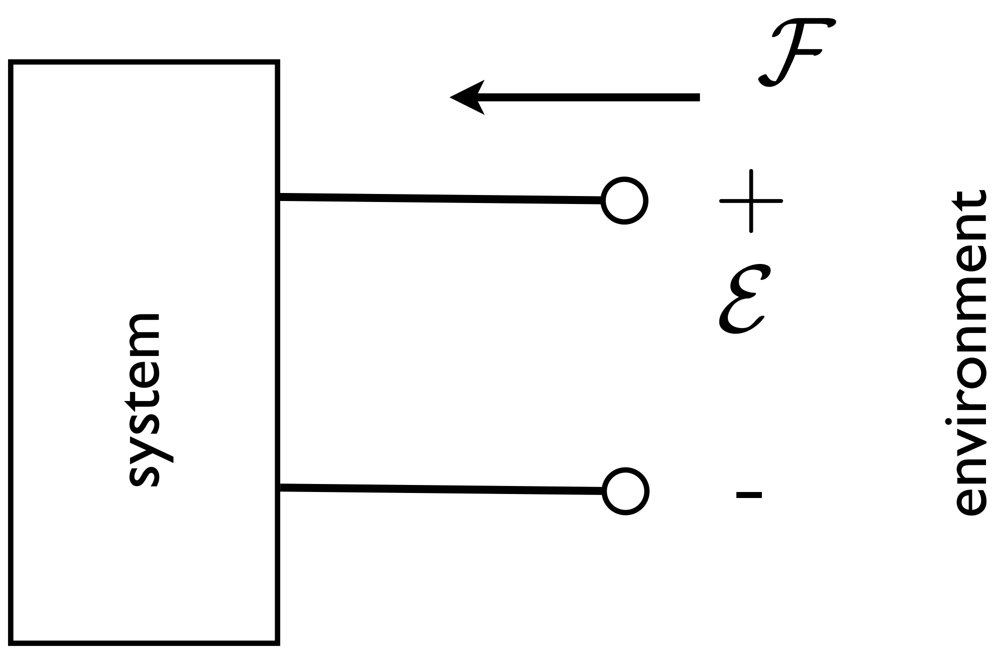
LTI continous systems can be described by the relationships between effort and flow variables

	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

and similarities between variables

electrical			mechanical	
voltage	$v(t)$	$\simeq$	force	$f(t)$
current	$i(t)$		velocity	$V(t)$
resistance	R		viscous friction	b
inductance	L		inertia	M
capacitance	$1/C$		stiffness	K
one-port impedance	Z		series/parallel of previous elements	$f(s)=Z(s)V(s)$

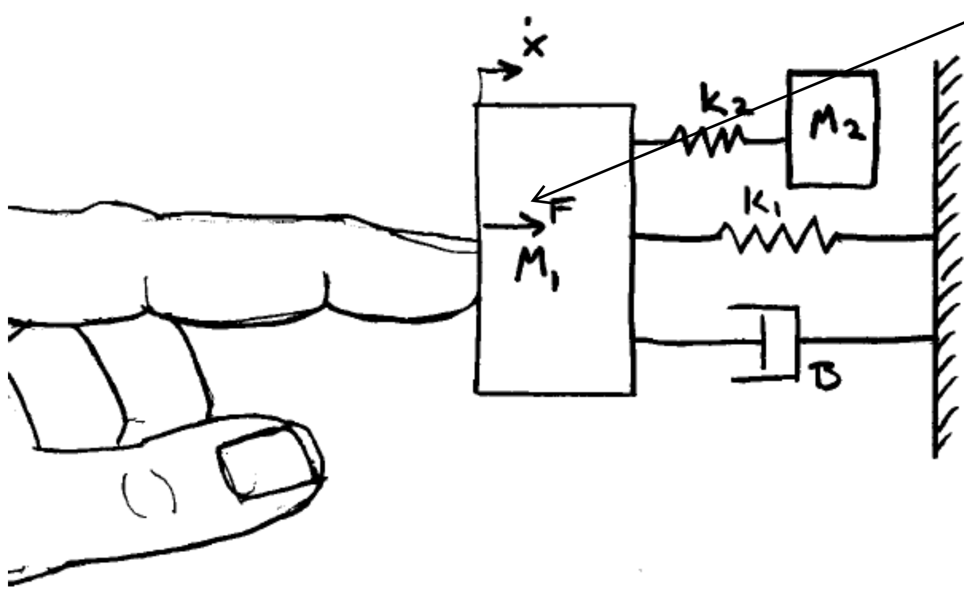
one-port network

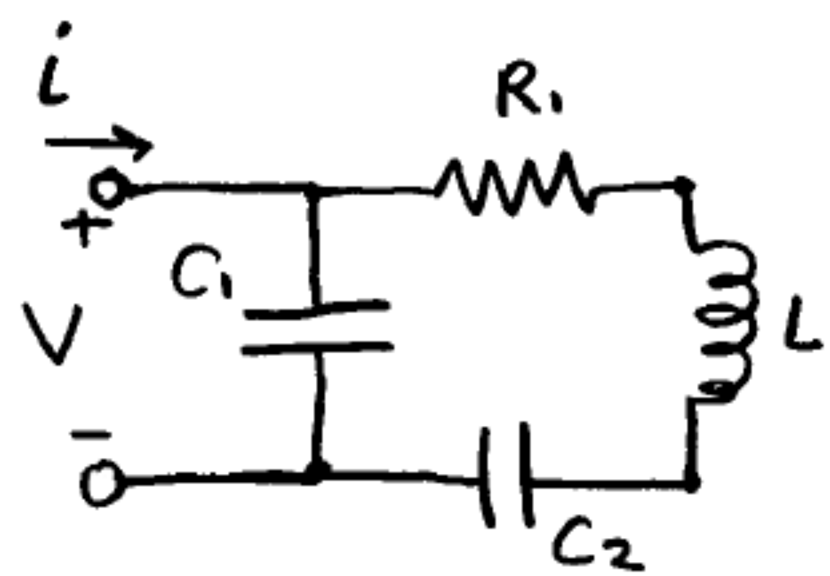


- effort and flow define positive or negative power going into the network at a single location where energy exchange takes place
- signs of effort and flow are usually defined so that power is positive flowing into the port (effort of interest: *on* the port)

F is positive when applied to the system

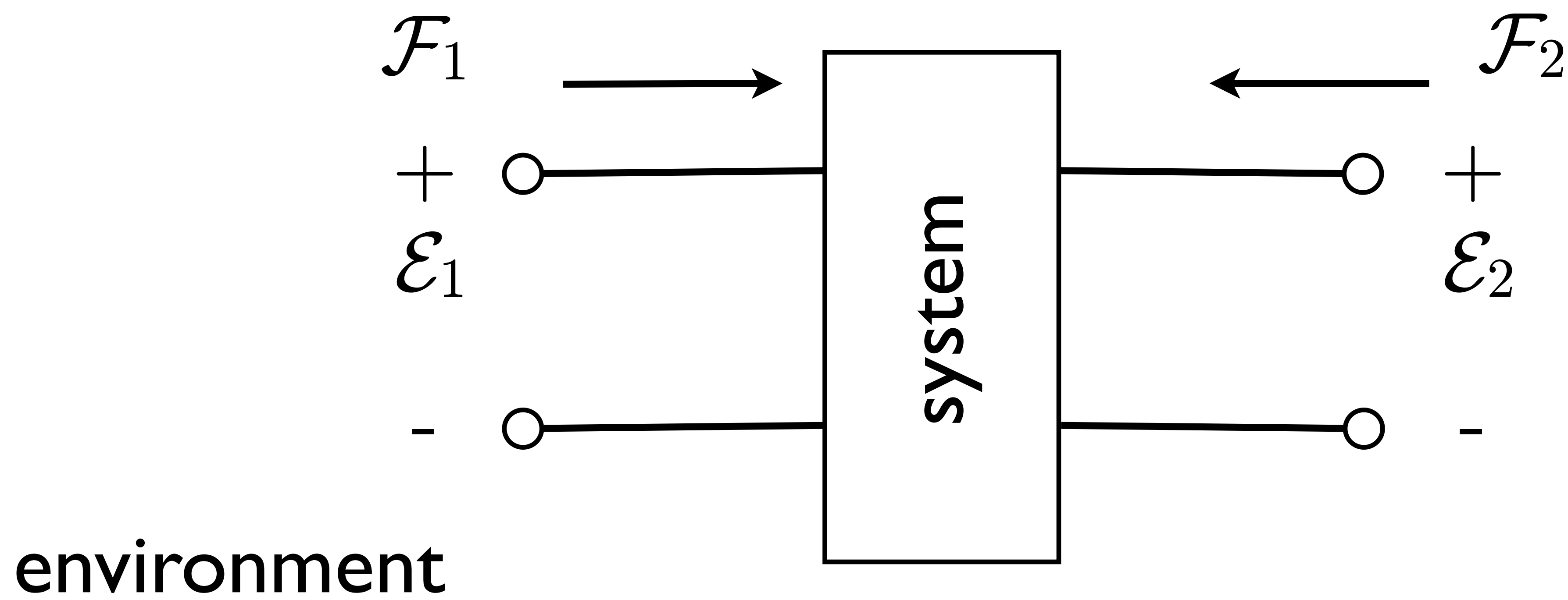
- examples of same convention: mechanical (MSD system), electrical (RCL)



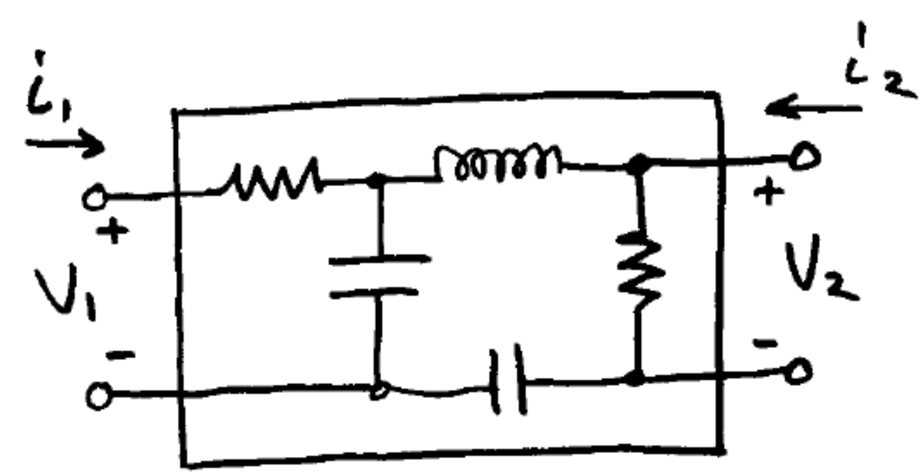


two-port network

forces are positive when enter the system

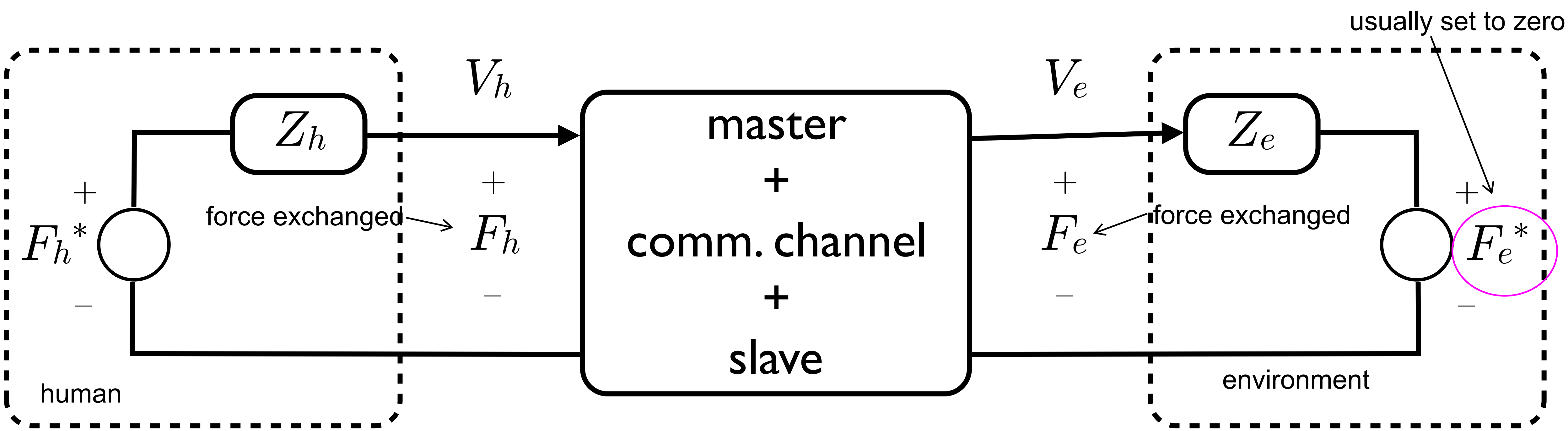


- two-ports have separate effort and flow variables, defined for each port, and a separate coordinate system (sign convention) for each port
- example of same convention: electric network



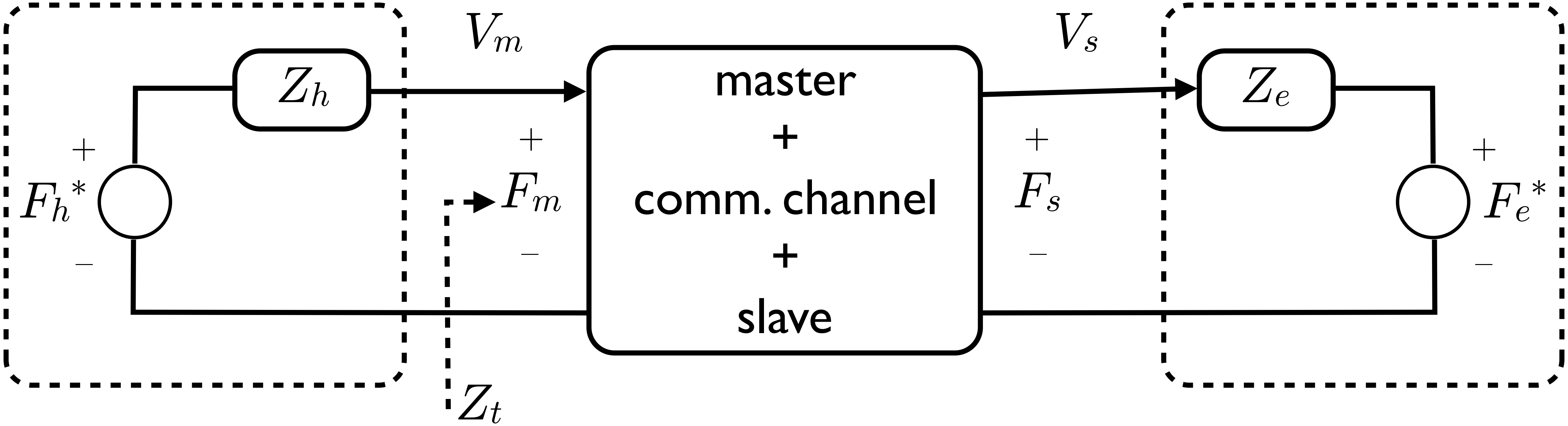
two-port model of teleoperator

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



F_h^*, F_e^* exogenous force inputs generated by the operator and the environment respectively; here we assume $F_e^*=0$ (passive environment)

two-port model of teleoperator



Z_t the transmitted impedance (i.e., seen by the human) and send back to the human

velocity of master manipulator when
is in contact with the human

$$\boxed{F_m = Z_t V_m}$$

interaction force between the
master manipulator and the human

ideally Zt = Ze

$$\boxed{F_s = Z_e V_s}$$

at the master side we would like to perceive the same impedance of the environment to have the perception to be there

- in the two-port model the behavior of the system is completely characterized by measurements of the forces and velocities at the two ports

4 variables to put in realtion each others

$$F_s = Z_e V_s \quad F_m = Z_t V_m$$

it depends also on the communication channel

- of these four involved variables, two may be chosen as independent and the remaining two dependent
- dependent variables are related to independent ones through the
  - impedance $(F_m, F_s, t) = \boldsymbol{Z}(V_m, V_s, t)$
    - elements of Z can be found through experiments
  - admittance $(V_m, V_s, t) = \boldsymbol{Y}(F_m, F_s, t)$
  - hybrid $(F_m, V_s, t) = \boldsymbol{H}(V_m, F_s, t)$ or $(F_m, V_m, t) = \boldsymbol{H}(V_s, F_s, t)$
  - scattering $(\boldsymbol{F}\text{-}b\boldsymbol{V}, t) = \boldsymbol{S}(\boldsymbol{F}+b\boldsymbol{V}, t)$ coordinate transformation that combines flow and effort master and slave. It is particular useful when we deal with delay in the transmission system.

operators (transfer matrices for LTI systems)

Linear Time Invariant

transparency

for the same forces $F_s = F_m$ we want the same motion $V_s = V_m$

$$\Downarrow$$

transparency condition $Z_t = Z_e$

- what degree of transparency is possible?
- what are suitable teleoperator architecture and control laws for achieving necessary or optimal transparency?

for the analysis consider the linearized behavior around contact-operating point using the hybrid matrix formulation (Lawrence)

transfer function (s is the Laplace variable)

the hibrid matrix is also the transparency matrix

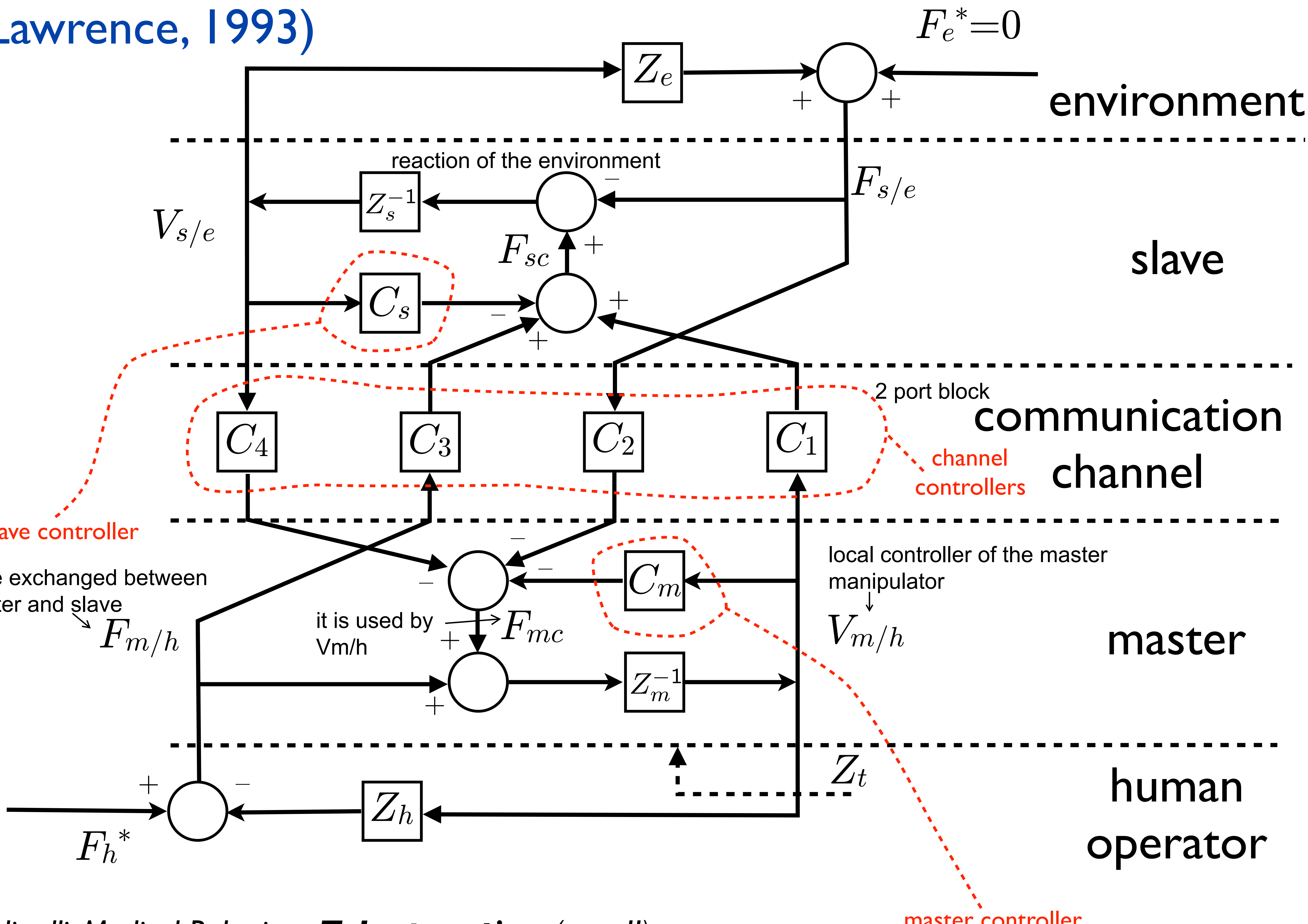
$$\begin{bmatrix} F_m(s) \\ V_m(s) \end{bmatrix} = \begin{bmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{bmatrix} \begin{bmatrix} V_s(s) \\ -F_s(s) \end{bmatrix}$$

entries of the hibrid representation

$$\boxed{F_m = (H_{11} - H_{12} Z_e)\ (H_{21} - H_{22} Z_e)^{-1} V_m}$$

it considers always start from the 1-2 port representation of the tele operator. 4 channels makes reference to the 4 possible signals that can be exchanged between master and slave.

a general 4-channel architecture
(Lawrence, 1993)



the blocks are specified for the two simple teleoperation control scheme seen in the last lecture

blocks of the 4-channel architecture for position-position and position-force control schemes

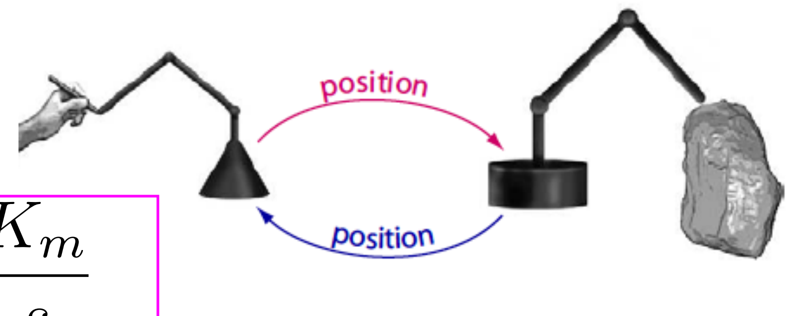
C2(communication) and C3control because they transmit the interaction forces from the slave to the master and viceversa in the posiotion-position architecture.

block	position-position	position-force
master impedance Z_m	$M_m s$	$M_m s$
master controller C_m	friction $B_m + K_m/s$ elesticity	B_m
slave impedance Z_s	$M_s s$	$M_s s$
slave controller C_s	$B_s + K_s/s$	$B_s + K_s/s$
velocity channel C_1	$B_s + K_s/s$	$B_s + K_s/s$
force channel C_2	not used	K_f
force channel C_3	not used	not used
velocity of the slave to the master velocity channel C_4	$-(B_m + K_m/s)$	not used
operator impedance Z_h	not a function of	control architecture
task impedance Z_e	not a function of	control architecture

Example: position-position vs the 4-channel architecture

master

- impedance $\boxed{Z_m = M_m s}$
- controller $\boxed{C_m = B_m + \frac{K_m}{s}}$



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slave

- impedance $Z_s = M_s s$
- controller $C_s = B_s + \frac{K_s}{s}$

dumping coeff and stiffnes of the slave controller

velocity channel $C_1 = B_s + K_s/s$

velocity channel $C_4 = -(B_m + K_m/s)$

force channels C_2 and C_3 not used

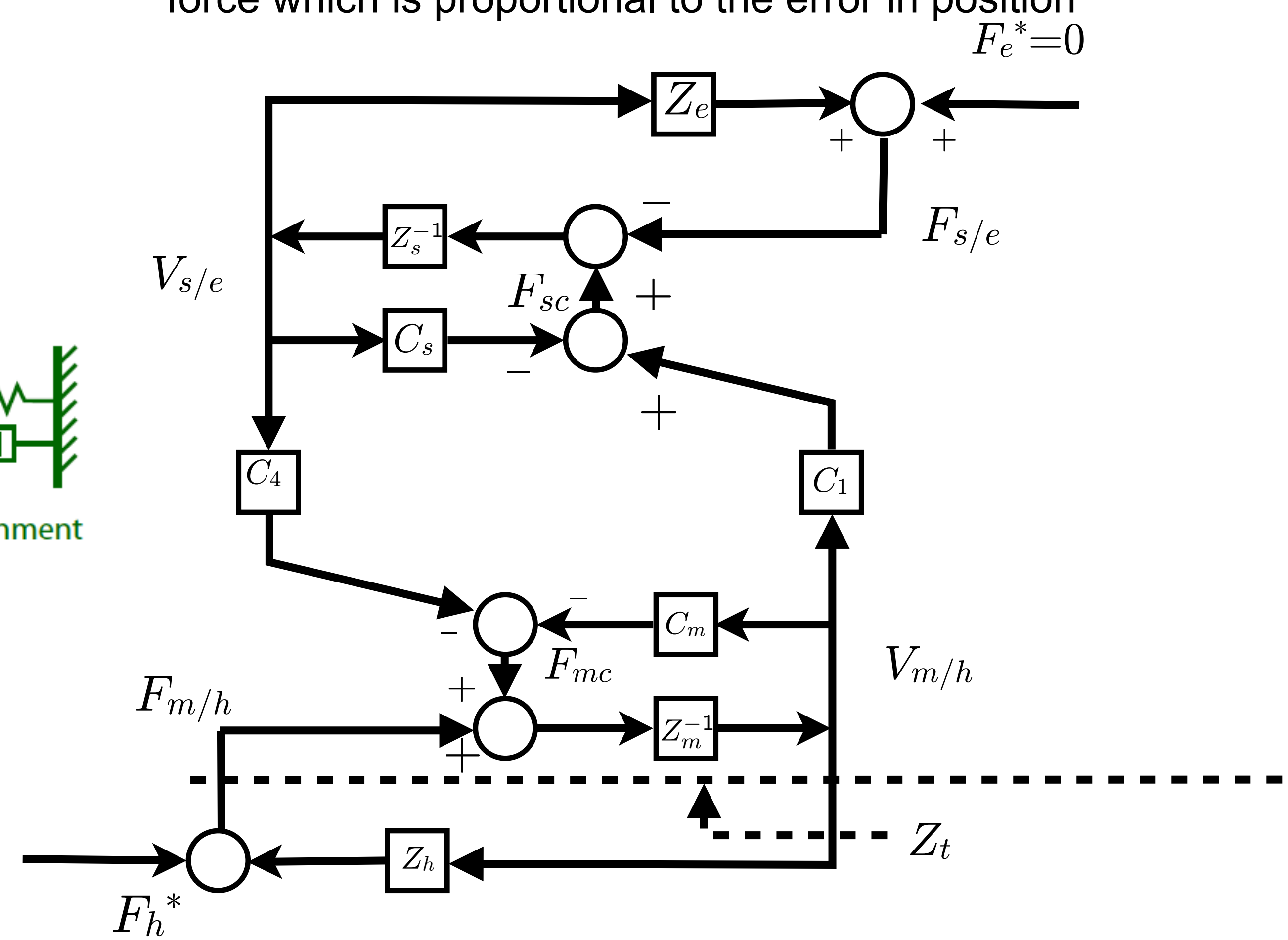
$\Rightarrow$

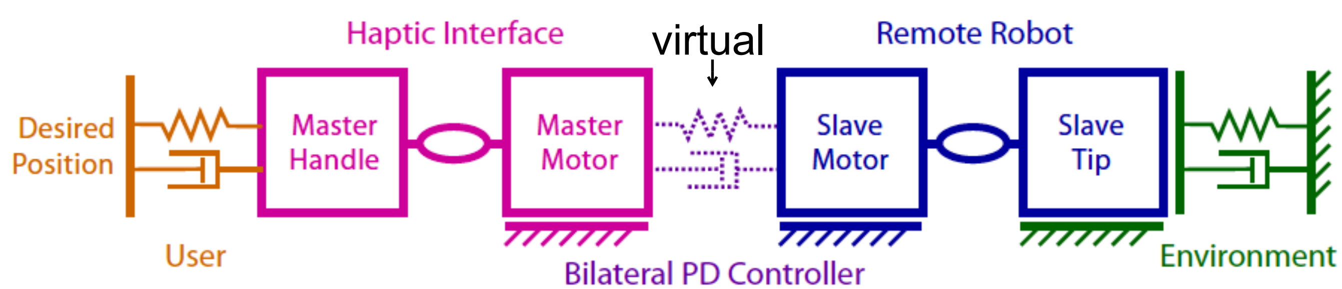
$F_{mc} = -C_m V_h - C_4 V_e = (B_m + K_m/s)\ (V_e - V_h)$

the same but with opposite sign

$F_{sc} = -C_s V_e - C_1 V_h = (B_s + K_s/s)\ (V_h - V_e)$

stifness which integrates the error in velocit so we have a force which is proportional to the error in position





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- solving for the transfer functions between master and slave forces and velocities Hij on function of four channel (communication channel C)

$$H_{11} = (Z_m + C_m) D (Z_s + C_s - C_3 C_4) + C_4$$
$$H_{12} = -(Z_m + C_m) D (I - C_3 C_2) - C_2$$
$$H_{21} = D (Z_s + C_s - C_3 C_4) - C_2$$
$$H_{22} = -D (I - C_3 C_2)$$
$$D = (C_1 + C_3 Z_m + C_3 C_m)^{-1}$$

- these expressions can be used to
  - design suitable control laws $C_i (i = 1, \ldots, 4, m, s)$
  - design suitable master and slave (Z_m, Z_s)
  - compare transparency performance of different teleoperation architectures
  - improve or optimize transparency

optimizing for transparency

transmitted impedance

- being $Z_t = (H_{11} - H_{12} Z_e)\,(H_{21} - H_{22} Z_e)^{-1}$
- perfect transparency ($Z_t = Z_e$) can be obtained by choosing C_i $(i=1,\ldots,4)$ s.t. $H_{22}=0,\ H_{11}=0,\ H_{12}=I,\ H_{21}=-I$:

to have perfect transparency we need to assign values to the channels

- $C_3 C_2 = I, C_4 = -(Z_m + C_m),\ C_1 = (Z_s + C_s),\ C_2 = I$ ($C_2 \neq I$ for telefunctioning) ($\Rightarrow$a true 4-channel architecture)
- but $C_4 = -(Z_m + C_m),\ C_1 = (Z_s + C_s)$ require acceleration measurements (see $Z_{m/s}$ and $C_{m/s}$ in slide 19)
- at low frequencies good transparency can be achieved only with position and velocity measurements so without acceleration measurement
- in any case, stability is an issue

CONTINUA DA QUI SUL BLOCCO 14

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