Summary

- Telerobotics: a brief history
- Control Problems
- Modelling a telemanipulation systems
- Control Schemes
- A comparison
- Conclusions
Some control schemes:
- Force Reflection (FR)
- Position Error (PE)
- Shared Compliance Control (SCC)
- Passive Force Reflection (PFR)
- Four Channels (4C)
- Adaptive Motion/Force Control (AMFC)
- Sliding Mode Control (SMC)
- Predictive Control (PC)
- Passive Predictive Control (PPC)
- Intrinsically Passive Control (IPC)
- ...
Control Schemes – Intrinsically Passive Control

This scheme is based on passivity concepts. The controller is “built” with passive elements and its implementations can be interpreted in terms of passive physical components such as masses, dampers and springs. A possible expression of the control equations is:

\[
\begin{align*}
    f_{mc} - f_{mi} &= (m_{mc}s^2 + b_{mc}s)x_{mc} \\
    f_{mi} &= k_{mi}(x_m - x_{mc}) \\
    f_{mi} &= (k_{mi} + b_{mi}s)(x_{mc} - v_{mi}/s) \\
    f_{si} - f_{sc} &= (m_{sc}s^2 + b_{sc}s)x_{sc} \\
    f_{sc} &= k_{sc}(x_{sc} - x_s) \\
    f_{si} &= (k_{si} + b_{si}s)(v_{si}/s - x_{sc})
\end{align*}
\]

where \( m_{mc}, b_{mc}, k_{mc}, k_{mi}, b_{mi}, m_{sc}, b_{sc}, k_{sc}, k_{si}, b_{si} \) are the parameters of the controller; \( x_{mc}, x_{sc} \) are the positions of the virtual masses implemented in the controllers; \( f_{mi}, v_{mi}, f_{si}, v_{si} \) are forces and velocities exchanged between master and slave.
Control Schemes – Intrinsically Passive Control

Some problems:

- A twist or a wrench is not just a “vector” of 6 “scalar quantities”

- Imposition of not only translational movements (rotational velocities)

- Perception of torques (not only linear forces)

- Generalization to the geometric case (3D) of springs and dampers
Control Schemes – Intrinsically Passive Control

**Force**

\[ f = k \delta x \]

**Energy Function**

\[ W_C = \begin{bmatrix} R_r^T K_t (p_r - p_v) \\ \Lambda_o R_v^T R_r - R_r^T R_v \Lambda_o \end{bmatrix} \]

**Torque**
Control Schemes – Intrinsically Passive Control

**SPATIAL DAMPING FAMILY**

\[
W_D = \begin{bmatrix}
R_r^T B_t (R_r v_r - R_v v_v) \\
(\omega_r - \omega_v) \Lambda_o + \Lambda_o (\omega_r - \omega_v)
\end{bmatrix}
\]

\[
f = k \dot{x}
\]
Moreover, scattering variables are used in the communication channel in order to interconnect only passive terms,

\[
\begin{align*}
S_m^+ &= \frac{(f_{mi} + b_i v_{mi})}{\sqrt{2b_i}} \\
S_m^- &= \frac{(f_{mi} - b_i v_{mi})}{\sqrt{2b_i}} \\
S_s^+ &= \frac{(f_{si} + b_i v_{si})}{\sqrt{2b_i}} \\
S_s^- &= \frac{(f_{si} - b_i v_{si})}{\sqrt{2b_i}}
\end{align*}
\]

where \(b_i\) represents the impedance of the channel. The transmitted variables are

\[
S_s^+ = e^{-sT} S_m^+ , \quad S_m^- = e^{-sT} S_s^-
\]
Control Schemes – Intrinsically Passive Control

The diagram illustrates a control scheme where the master and slave systems interact through a communication channel. The master system is connected to the slave system, which in turn is connected to the environment. The human operator provides input to the system through the communication channel. The diagram shows the flow of information and control in this passive control setup.
Control Schemes – Intrinsically Passive Control

IPC concepts applied to remote control of robotic systems

Application to industrial arm;
Improvement of performance:
Arcara, Melchiorri, ECC’01
Arcara, Melchiorri, J. RAS, 2002
Arcara, Melchiorri, Mechatronics Forum, 2002
Arcara, Melchiorri, MISTRAL, 2003

Tele-control of mobile robots:
Diolaiti, Melchiorri, SYROCO’03

Without force feedback
With force feedback
Control Schemes – Intrinsically Passive Control

Screwing a bolt

Delay
Control Schemes – Intrinsically Passive Control

Turning a grip handle
Control Schemes – Intrinsically Passive Control

- Remote control of a mobile robot
Control Schemes – A comparison

- It is of interest to establish general criteria by means of which control schemes for telemanipulation systems can be evaluated and compared.

- These criteria should consider the performance achieved by the different schemes. In particular, five different aspects can be considered:
  - stability;
  - inertia and damping;
  - tracking;
  - stiffness;
  - drift.

- Stability and performance are always aspects in conflict, and the choice of the control parameters is often the result of a trade-off between them.
Control Schemes – A comparison

- **Inertia and damping:**
  \[
  G_1(s) \equiv \left( \frac{x_m}{f_h} \bigg|_{f_e=0} \right)^{-1}
  \quad G_1(s) = m_{eq}s^2 + b_{eq}s + G_1^*(s)
  \lim_{s \to 0} G_1^*(s)/s^2 = 0
  \]

- **Tracking:**
  \[
  G_2(s) \equiv \frac{x_m - x_s}{f_h} \bigg|_{f_e=0}
  \quad G_2(s) = \delta \, G_2^*(s)
  \quad G_2^*(0) = 1
  \]

- **Stiffness:**
  \[
  G_3(s) \equiv \left( \frac{x_m}{f_h} \bigg|_{f_e=-(b_{es}+k_e)x_s} \right)^{-1}
  \quad G_3(s) = k_{eq} \, G_3^*(s)
  \quad G_3^*(0) = 1
  \]

- **Drift**
  \[
  G_4(s) \equiv \frac{x_m - x_s}{f_h} \bigg|_{f_e=-(b_{es}+k_e)x_s}
  \quad G_4(s) = \Delta \, G_4^*(s)
  \quad G_4^*(0) = 1
  \]
Control Schemes – Intrinsically Passive Control

- IPC control law (scalar case):

\[
\begin{align*}
    f_{mc} - f_{mi} &= (m_{mc}s^2 + b_{mc}s)x_{mc} \\
    f_{mc} &= k_{mc}(x_m - x_{mc}) \\
    f_{mi} &= (k_{mi} + b_{mi}s)(x_{mc} - v_{mi}/s) \\
    f_{si} - f_{sc} &= (m_{sc}s^2 + b_{sc}s)x_{sc} \\
    f_{sc} &= k_{sc}(x_{sc} - x_s) \\
    f_{si} &= (k_{si} + b_{si}s)(v_{si}/s - x_{sc})
\end{align*}
\]
# Control Schemes – A comparison

### Criteria for the IPC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia ($m_{eq}$)</td>
<td>$2(m_m + m_{mc}) + b_i T - \frac{(b_m + b_{mc})^2 T}{b_i} + \ldots$ $\frac{2b_{mc}^2 (2k_{mi} + k_{mc}) + 2b_m (k_{mi} + k_{mc}) (b_m + 2b_{mc})}{k_{mi}k_{mc}}$</td>
</tr>
<tr>
<td>Damping ($b_{eq}$)</td>
<td>$2(b_m + b_{mc})$</td>
</tr>
<tr>
<td>Tracking ($\delta$)</td>
<td>$\frac{2b_i (k_{mi} + k_{mc}) + k_{mi} k_{mc} T}{2b_i k_{mi} k_{mc}}$</td>
</tr>
<tr>
<td>Stiffness ($k_{eq}$)</td>
<td>$\frac{k_e b_i k_{mi} k_{mc}}{b_i (k_{mi} k_{mc} + 2k_e (k_{mi} + k_{mc})) + k_e k_{mi} k_{mc} T}$</td>
</tr>
<tr>
<td>Drift ($\Delta$)</td>
<td>$\frac{2b_i (k_{mi} + k_{mc}) + k_{mi} k_{mc} T}{b_i k_{mi} k_{mc}}$</td>
</tr>
</tbody>
</table>
Selection of suitable control parameters:

Same criteria can be applied to other control schemes...

Force Reflection (FR); Position Error (PE); Shared Compliance Control (SCC); Passive Force Reflection (PFR): Four Channels (4C); Adaptive Motion/Force Control (AMFC); Sliding Mode Control (SMC); Predictive Control (PC); Passive Predictive Control (PPC); Intrinsically Passive Control (IPC)
This is perhaps the first control scheme appeared in the literature and probably the most intuitive for its simplicity. Position information is transmitted from master to slave, and a force feedback from slave to master is present. The control equations are:

\[
\begin{align*}
    f_{mc} &= g_c f_{sd} \\
    f_{sc} &= k_c (x_{md} - x_s)
\end{align*}
\]

where \( g_c \) and \( k_c \) are control parameters. Subscript \( d \) indicates the (delayed) signal transmitted in the communication channel, and \( e^{-sT} \) represents the Laplace transformation of the constant delay \( T \) in the transmission channel.
This is a fully symmetric control scheme. The forces applied to the manipulators are proportional to the difference (error) between local position and received (delayed) remote position. In this scheme only position information is thus exchanged between master and slave. The control equations and the transmitted signals are:

\[
\begin{align*}
    f_{mc} &= g_c k_c (x_m - x_{sd}) \\
    f_{sc} &= k_c (x_{md} - x_s)
\end{align*}
\]

\[
\begin{align*}
    x_{md} &= e^{-sT} x_m \\
    x_{sd} &= e^{-sT} x_s
\end{align*}
\]

Kim, W.S., ICRA’92
Shared compliance control is very similar to the FR scheme, the only difference being a compliance term inserted in the controller at the remote side to modify the behaviour of the slave manipulator according to the interaction with the environment. The control equations become:

\[
\begin{align*}
    f_{mc} &= g_c f_{sd} \\
    f_{sc} &= k_c (x_{md} - x_s + G_f(s) f_e) \\
    x_{md} &= e^{-sT} x_m, \\
    f_{sd} &= e^{-sT} f_{sc}
\end{align*}
\]

where \(g_c, k_c\) are control parameters and \(G_f(s)\) represents the transfer function of a low-pass filter.
The FR control scheme can be modified by adding one or more dissipative elements in order to guarantee the passivity ("damping injection"). The control equations become:

\[
\begin{align*}
    f_{mc} &= g_c f_{sd} + b_i v_m \\
    f_{sc} &= k_c \left( \frac{v_{md} - f_{sc}/b_i}{s} - x_s \right)
\end{align*}
\]

where \( v_m = s x_m \) represents the velocity of the master and \( k_c, g_c, b_i \) are control parameters.

This is a telemanipulation control scheme in which both velocity and force information are exchanged between master and slave. The control is defined as:

\[
\begin{align*}
\mathbf{f}_{mc} &= -c_6 f_h + c_m \mathbf{v}_m + f_{sd} + \mathbf{v}_{sd} \\
\mathbf{f}_{sc} &= c_5 f_e - c_s \mathbf{v}_s + f_{md} + \mathbf{v}_{md}
\end{align*}
\]

where \( \mathbf{v}_m = s \mathbf{x}_m \), \( \mathbf{v}_s = s \mathbf{x}_s \) are velocities; \( c_5, c_6 \) are feedforward and \( c_m, c_s \) feedback control parameters. As concerns the transmitted information, there are four "channels":

\[
\begin{align*}
\mathbf{v}_{md} &= c_1 e^{-sT} \mathbf{v}_m \\
\mathbf{f}_{sd} &= c_2 e^{-sT} f_s \\
\mathbf{f}_{md} &= c_3 e^{-sT} f_m \\
\mathbf{v}_{sd} &= c_4 e^{-sT} \mathbf{v}_s
\end{align*}
\]

where \( c_1, c_2, c_3, c_4 \) are parameters of the communication line.

The scheme can be simplified by a proper parameters choice.
As in the four-channels scheme, velocity and force are exchanged in the communication line. Moreover, each manipulator has its own local adaptive position/force control, where the parameters of the manipulator are locally estimated. The master and slave controllers are:

\[
\begin{align*}
    f_{mc} &= -\frac{ac}{s+c}G_m(s)f_h + (C_m(s) + \frac{\lambda}{s}G_m(s))v_m - f_{sd} - v_{sd} \\
    f_{sc} &= \frac{ac}{s+c}G_s(s)f_e - (C_s(s) + \frac{\lambda}{s}G_s(s))v_s + f_{md} + v_{md}
\end{align*}
\]

where \(a, c, \lambda\) are constant parameters; \(G_i(s)\) and \(C_i(s)\), \(i=m, s\), are feedforward and feedback controllers (\(k_i, k_{i1}\) are PI feedback gains); \(\hat{m}_i, \hat{b}_i\) are the estimated values of the mass and damping parameters of the manipulators (computed on-line). There are four different transmission channels:

\[
\begin{align*}
    v_{md} &= \frac{c(s+\lambda)}{s(s+c)}G_s(s)e^{-sT}v_m, & f_{sd} &= \frac{ac}{s+c}G_m(s)e^{-sT}f_e \\
    f_{md} &= \frac{ac}{s+c}G_s(s)e^{-sT}f_h, & v_{sd} &= \frac{c(s+\lambda)}{s(s+c)}G_m(s)e^{-sT}v_s
\end{align*}
\]

Control Schemes – Sliding Mode Control

- The variable structure control offers robustness against uncertainties and, moreover, can be used to deal with problems arising with time delay. A sliding-mode controller is defined at the slave side in order to achieve a perfect tracking in finite time of the delayed master position, while at the master side an impedance controller is used. The corresponding control equations are:

\[
\begin{align*}
    f_{mc} &= f_h - b_m v_m + \frac{m_m}{m_c} (b_c v_m + k_c x_m - f_h - f_{ed}) \\
    f_{sc} &= -f_e + b_s v_s - \frac{m_s}{m_c} (b_c v_{md} + k_c x_{md} - f_{hd} - f_{edd}) + \\
    &\quad -m_s \lambda \dot{e} - k_g \text{sat}(\frac{S}{\phi})
\end{align*}
\]

where \( m_c, b_c, \) and \( k_c \) are the impedance controller parameters; \( \lambda \) and \( k_g \) the sliding-mode parameters; \( e=x_s-x_{md} \) is the slave position error; \( S=\dot{e}+\lambda e \) the sliding surface; \( \text{sat}(\cdot) \) represents the saturation function. Four variables are transmitted from master to slave, and one \( (f_e) \) from slave to master:

\[
\begin{align*}
    x_{md} &= e^{-sT} x_m, \quad v_{md} = e^{-sT} v_m \\
    f_{hd} &= e^{-sT} f_h, \quad f_{edd} = e^{-sT} f_{edd} \\
    f_{ed} &= e^{-sT} f_e
\end{align*}
\]

In the control methods described above, information from the remote site is used as feedback to the master, but no knowledge about the slave dynamics is required in the design of the master controller. Conversely, it is possible to consider explicitly the remote dynamics into the local controller in order to predict the slave behavior. The following algorithm, in particular, is based on the well known Smith predictor scheme. The controllers are

\[
\begin{align*}
 f_{mc} &= g_c \left[ \frac{(m_s s^2 + b_s s) (b_c s + k_c)}{m_s s^2 + (b_s + b_c) s + k_c} (1 - e^{-2sT}) x_m + f_{sd} \right] \\
 f_{sc} &= (b_c s + k_c) (x_{md} - x_s)
\end{align*}
\]

The prediction term is evident in the first expression (master control law). $g_c$, $b_c$ and $k_c$ are control parameters. The transmitted variables are the same as in the FR scheme:

\[
x_{md} = e^{-sT} x_m, \quad f_{sd} = e^{-sT} f_{sc}
\]

T.B. Sheridan, IEEE TRA, 1993
This method combines the Smith predictor and the scattering variables to achieve both the benefits of the performance and stability. Let $f_{mc}$, $v_{mc}$, $f_{sc}$, $v_{sr}$ be forces and velocities exchanged between master and slave. In order to guarantee passivity, these signals are transformed in wave variables:

$$\begin{align*}
U_m &= (f_{mc} + b_i v_m)/\sqrt{2b_i} \\
V_m &= (f_{mc} - b_i v_m)/\sqrt{2b_i}
\end{align*}$$

$$\begin{align*}
U_s &= (f_{sc} + b_i v_{sr})/\sqrt{2b_i} \\
V_s &= (f_{sc} - b_i v_{sr})/\sqrt{2b_i}
\end{align*}$$

where $b_i$ is the impedance of the channel. The transmitted variables are

$$U_s = e^{-sT} U_m, \quad V_a = e^{-sT} V_s$$

where the signal $V_s$ from the slave becomes the input $V_a$ of the Smith predictor at the master that calculates the wave variable $V_m$ as

$$V_m = \text{Regulator}[G_p(s)(1 - e^{-2sT})U_m + V_a]$$

$G_p(s)=V_s/U_s$ represents the transfer function of the entire slave site (the slave manipulator, the PD controller, the wave transformation); the regulator is inserted to guarantee passivity: in particular, passivity definition is satisfied since the energy associated with the returning wave $V_m$ is always not greater than the energy associated with the outgoing wave $U_m$.

The PD controller implemented at the slave is

$$f_{sc} = (b_cs + k_c) \left( \frac{v_{sr} - v_s}{s} \right)$$

where $b_c$ and $k_c$ are parameters.
## Control Schemes – Inertia and Damping

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Inertia ($m_{eq}$)</th>
<th>Damping ($b_{eq}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR</td>
<td>$(1 + g_c)m_m - g_c b_m \left( \frac{b_m}{k_c} + 2T \right)$</td>
<td>$(1 + g_c)b_m$</td>
</tr>
<tr>
<td>PE</td>
<td>$2(m_m - b_m T - k_c T^2) - \frac{b_m^2}{k_c}$</td>
<td>$2(b_m + k_c T)$</td>
</tr>
<tr>
<td>SCC</td>
<td>$(1 + g_c)m_m - g_c b_m \left( \frac{b_m}{k_c} + 2T \right)$</td>
<td>$(1 + g_c)b_m$</td>
</tr>
<tr>
<td>PFR</td>
<td>$\left(1 + \frac{g_c b_i^2}{(b_m + b_i)^2}\right)m_m - \frac{2g_c b_i b_m T}{b_m + b_i} - \frac{g_c b_i b_m^2}{(b_m + b_i)^2 k_c}$</td>
<td>$b_m + b_i + \frac{g_c b_i b_m}{b_m + b_i}$</td>
</tr>
<tr>
<td>IPC</td>
<td>$2(m_m + m_{mc}) + b_i T - \frac{(b_m + b_{mc})^2 T}{b_i} + \ldots$</td>
<td>$2(b_m + b_{mc})$</td>
</tr>
<tr>
<td></td>
<td>$\ldots - \frac{2b_{mc}^2(2k_m + k_{mc}) + 2b_m(k_m + k_{mc})(b_m + 2b_{mc})}{k_m k_{mc}}$</td>
<td></td>
</tr>
<tr>
<td>4C</td>
<td>$\frac{2T(b_m + c_m)}{c_2 + c_3}$</td>
<td>0</td>
</tr>
<tr>
<td>AMFC</td>
<td>$\frac{2ak_m(1 + cT) + \lambda(-1 - cT + ak_m T)}{2a^2 c k_m}$</td>
<td>$\frac{\lambda(1 + cT)}{ac}$</td>
</tr>
<tr>
<td>SMC</td>
<td>$\frac{m_c}{b_c}$</td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td>$(1 + g_c)m_m - \frac{g_c b_m^2}{k_c}$</td>
<td>$(1 + g_c)b_m$</td>
</tr>
<tr>
<td>PPC</td>
<td>$2m_m - \frac{b_m^2}{k_c}$</td>
<td>$2b_m$</td>
</tr>
</tbody>
</table>
## Control Schemes – Tracking & Stiffness

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Tracking $(\delta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR</td>
<td>$\frac{b_m + k_c T}{b_mk_c(1 + g_c)}$</td>
</tr>
<tr>
<td>PE</td>
<td>$\frac{1}{2g_ck_c}$</td>
</tr>
<tr>
<td>SCC</td>
<td>$\frac{b_m + k_c T}{b_mk_c(1 + g_c)}$</td>
</tr>
<tr>
<td>PFR</td>
<td>$\infty$</td>
</tr>
<tr>
<td>IPC</td>
<td>$\frac{2b_i(k_{mi} + k_{mc}) + k_{mi}k_{mc}T}{2b_i k_{mi}k_{mc}}$</td>
</tr>
<tr>
<td>4C</td>
<td>$\frac{2(b_m + c_m)}{c_2 - c_3}$</td>
</tr>
<tr>
<td>AMFC</td>
<td>0</td>
</tr>
<tr>
<td>SMC</td>
<td>0</td>
</tr>
<tr>
<td>PC</td>
<td>$\frac{b_m + k_c T}{b_mk_c(1 + g_c)}$</td>
</tr>
<tr>
<td>PPC</td>
<td>$\frac{b_m + k_c T}{2b_mk_c}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Stiffness $(k_{eq})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR</td>
<td>$\frac{k_eg_ck_c}{k_e + k_c}$</td>
</tr>
<tr>
<td>PE</td>
<td>$\frac{k_eg_ck_c}{k_e + k_c}$</td>
</tr>
<tr>
<td>SCC</td>
<td>$\frac{k_e + k_c}{k_e g_c k_c}$</td>
</tr>
<tr>
<td>PFR</td>
<td>0</td>
</tr>
<tr>
<td>IPC</td>
<td>$\frac{k_e b_i k_{mi} k_{mc}}{b_i(k_{mi} k_{mc} + 2k_e (k_{mi} + k_{mc})) + k_e k_{mi} k_{mc} T}$</td>
</tr>
<tr>
<td>4C</td>
<td>$\frac{k_e (c_2 + c_3) (b_m + c_m)}{(c_2 + c_3)(b_m + c_m) + 2k_e c_2 c_3 T}$</td>
</tr>
<tr>
<td>AMFC</td>
<td>$k_e$</td>
</tr>
<tr>
<td>SMC</td>
<td>$k_e + k_c$</td>
</tr>
<tr>
<td>PC</td>
<td>$\frac{k_eg_ck_c}{k_e + k_c}$</td>
</tr>
<tr>
<td>PPC</td>
<td>$\frac{k_e k_c (b_i + b_m)}{(k_e + k_c)(b_i + b_m) + 2k_e k_c T}$</td>
</tr>
</tbody>
</table>
## Control Schemes - Drift

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Drift ($\Delta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR</td>
<td>$\frac{1}{g_c k_c}$</td>
</tr>
<tr>
<td>PE</td>
<td>$\frac{1}{g_c k_c}$</td>
</tr>
<tr>
<td>SCC</td>
<td>$\frac{1 + k_f k_c}{g_c k_c}$</td>
</tr>
<tr>
<td>PFR</td>
<td>$\infty$</td>
</tr>
<tr>
<td>IPC</td>
<td>$\frac{2b_i (k_m i + k_m c) + k_m i k_m c T}{b_i k_m i k_m c}$</td>
</tr>
<tr>
<td>4C</td>
<td>$\frac{b_i k_m i k_m c}{2c_2 c_3 T}$</td>
</tr>
<tr>
<td>AMFC</td>
<td>0</td>
</tr>
<tr>
<td>SMC</td>
<td>0</td>
</tr>
<tr>
<td>PC</td>
<td>$\frac{1}{g_c k_c}$</td>
</tr>
<tr>
<td>PPC</td>
<td>$\frac{b_i + b_m + 2k_c T}{(b_i + b_m)k_c}$</td>
</tr>
</tbody>
</table>
Control Schemes - Stability

The stability of a telemanipulation scheme is strongly related to the amount of time delay $T$ in the transmission channel. In practice, one can define two main cases:

- **IS** schemes which are *intrinsically stable*, that is stability is automatically guaranteed independently of time delay $T$.

- **PS** schemes which are *possibly stable*, i.e. that can be rendered stable, for any value of the delay $T$, with a proper choice of the controller's parameters.

<table>
<thead>
<tr>
<th></th>
<th>FR</th>
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Control Schemes – Some remarks

**Stability:**

One may observe that only the schemes based on passivity concepts intrinsically guarantee stability.

The FR, PE and SCC schemes can be made stable with a proper choice of control parameters, provided that $T < T_{\text{max}}$, i.e. only for limited values of time delay. Moreover, in general the maximum admissible delay $T_{\text{max}}$ increases from FR to PE and SCC (the latter offers better robustness properties in terms of stability).

The stability of the AMFC and SMC schemes strongly depends on the remote environment. PC stability is mainly related to a good knowledge of the remote slave manipulator and of the transmission delay $T$, because of the use of the Smith predictor within its control system.
Each telemanipulation scheme has both positive and negative aspects, and therefore it is hopefully possible to select the control scheme more suitable for the specific application under consideration. Some of the main aspects concerning the choice of a teleoperation scheme are:

- Available information on the transmission time delay $T$. In fact, the entity of the delay could be “small” (few milliseconds), “medium” (some tenths of second) or “high” (some seconds or more). Furthermore, the delay could be constant or variable, known or unknown, and, finally, it could be limited ($T < T_{\text{max}}$) or not.

- Desired performances, in terms of tracking properties at the slave manipulator and perception of the environment (correct force feedback).

- Implementation and the necessary equipment for the development of the telemanipulation controller. Available resources in terms of sensors, computing power, transmission bandwidth and so on are often crucial and they must be considered for the choice of a simple or of a more sophisticated control scheme.

- Knowledge of the environment structure and of the task to be carried out. In fact, the remote environment could be dissipative with no possibility of injecting energy, could have certain damping or stiffness properties, could have a maximum value for the exerted external force or, as extreme case, an operator exerting unpredictable forces could even be connected to the slave manipulator.

Only by paying attention to these (and other) aspects one can define a suitable telemanipulation scheme for the necessities at hand and, at least, eliminate those that cannot satisfy the given requirements.
Telemanipulation - Conclusions

As Walter Benjamin foresaw in 1936, we have an increasing urge to view and manipulate distant objects.

Tele-technologies, always useful for research and science, are increasingly relevant to our daily life.

Although important solutions and notable devices have been proposed, challenging problems still exist in:

- Control theory
- Equipment
- Use in real applications
Robotic Telemanipulation Systems: Control Aspects

The End

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