Advances in pHRI: development of a stiffness-mimicking adaptive impedance controller for teleoperation

Supervisor: Prof. Elena De Momi
Co-supervisor: Dr. Jacopo Buzzi

Candidate: Andrea Passoni
852543

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Teleoperated Robotic Systems

Advantages:

- Enhanced dexterity
- Manual tremor filtering
- Hand movements downscaling
- Additional degrees of freedom at the tips of the instruments
- High definition 3D vision
While manipulating the robotic master device, the human operator establishes a **physical interaction** with it.

**Human**
- Cognitive capabilities (High-level sub-tasks)
- Planning
- Adapting to uncertainties

**Robot**
- Low-level sub-tasks
- High precision
- High repeatability

**Human-Robot Interaction:** “study of humans, robots and the ways they influence each other”  
[Fong, T et al., 2001]
Humans perform a wide variety of movements by adjusting the dynamic characteristics of their musculoskeletal system in motion.

The dynamics of a hand-arm system has often been discussed by using mechanical impedance parameters.

- **Joint configuration of the limb**
  - $K = \Delta F / \Delta l$
- **Segmental reflexes**
  - Dominant component at low arm velocities
  - Vector field of restoring forces
  - Geometrically described as an ellipsoid

Muscle co-contraction

[Darainy, M et al., 2004; Gomi, H et al., 1998]
Teleoperation Control Schemes

Impedance control

- Main control paradigm adopted in teleoperation systems
- Exchanged forces between slave and environment are monitored and used to modify the master’s mechanical properties at contact

- Low viscous resistance of the master robot when the slave is unconstrained
- Higher target damping when the slave approaches a constraint surface, prior to contact

Hannaford and Anderson, 1988

Further step

Adaptive Impedance Control

Love et al., 2004

- Position control
- Earlier prototypes of master-slave teleoperation systems
- Limitations in dealing with interaction tasks in uncertain environments due to possible high forces at contact

HUMAN ARM
IMPEDEANCE
\( M_b, B_b, K_b \)

SLAVE ROBOT
CONTROLLER
\( x_s, x_e \)

SLAVE ROBOT
(H/W)
\( x_e \)

ENVIRONMENT
IMPEDEANCE
\( (K_e, x_e) \)

HAPTIC DISPLAY
CONTROLLER
\( x_m, x_n, x_{mn} \)

HAPTIC DEVICE
(H/W)
\( F_m, F_n \)

MASTER

\( x_m, x_{mn} \)
Problem Statement and Aim of the Work

1. Context
No research has tried to match the master device’s impedance with the human operator’s impedance.

2. Problem
Master Devices are completely unaware of the users’ dynamic changes.

3. Idea
Account for the human motor control strategies in the design of the master device to enhance pHRI and improve performances.

4. Aim
Development of an adaptive impedance controller able to mimic the human arm endpoint stiffness.

Andrea Passoni
andrea3.passoni@mail.polimi.it
The Workflow

- **Inverse Kinematics**
  - **JOINT ANGLES**
  - **PROCESSED EMG**
    - Filtered
    - Normalized
  - **Raw EMG**
  - **Raw markers movements**

- **USER**
  - **HUMAN ARM DYNAMIC MODEL**
  - **ARM ENDPOINT STIFFNESS ESTIMATION**

- **CONTROLLER**
  - **DYNAMIC MODEL**
  - **ARM ENDPOINT**

- **MASTER DEVICE**
  - **STIFFNESS**
  - **ADAPTIVE IMPEDANCE CONTROL**

- **REMOTE/VIRTUAL ENVIRONMENT**

Andrea Passoni
andrea3.passoni@mail.polimi.it
Arm Endpoint Stiffness Estimation – Experimental Setup

The task
- Reaching planar targeting task
- Developed using v-rep
- 7 recruited subjects
- 8 targets
- 10 repetitions

The master device
- Force Dimension Sigma 7 haptic device
- Hybrid parallel/serial link
- 6 DoFs + grip control

The musculoskeletal model
- 7 DoFs
- 50 Hill-type muscle-tendon actuators
- 32 muscle compartments
Arm Endpoint Stiffness Estimation – Experimental Setup

Acquisition Protocol

1. Task on a monitor laid flat
2. Master Device
3. Electromagnetic sensors
4. Optical camera
5. Bipolar electrodes
6. Electromagnetic tracker
7. Shoulder and virtual reference frames (grossly aligned)
8. Retro-reflective markers
9. shoulder and virtual reference frames (grossly aligned)
Arm Endpoint Stiffness Estimation – Computation Method

**OpenSim Model**

- Muscle Analysis
  - MTU Kinematics
  - Muscle Jacobian: $J_m = \frac{dl}{dq}$
  - Muscle Stiffness: $K_m = \frac{dF}{dl}$
  - Musculo-tendon moment arms
- Joint Torques: $\tau$
- Inverse Dynamics
  - Joint Angles: $q$
  - EMG signals
  - EMG-informed Inverse Dynamics
    - Band-pass filtered
    - Full-wave rectified
    - Low-pass filtered
- CEINMS
  - 7 DoFs Model
  - Geometric Jacobian: $J = \frac{dp}{dq}$
  - Joint Stiffness: $K_J = J_m^T K_m J_m$
  - Endpoint Cartesian Stiffness: $K_e = (J^{-1})^T K_J J^{-1}$
  - SVD
    - Principal axis magnitude and direction
Results – Arm Endpoint Stiffness Modulation (Magnitude)

Users showed a **common stiffness modulation strategy** while performing the reaching task:

- **First part of the reaching phase**
  - Users are still far from the target goal
  - Low and almost constant stiffness modulation profile

- **Second part of the reaching phase**
  - Users are approaching the target goal
  - Higher stiffness with an ascending linear trend

![Graph showing stiffness modulation over normalized distance](image)

\[
K_{\text{max}} [\text{N/m}] \\
\begin{array}{cccccccc}
0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 & 0.6 & 0.7 & 0.8 & 0.9 & 1 \\
\end{array}
\]

\[p = 0.887, \quad p = 0.0003\]
Results – Arm Endpoint Stiffness Modulation (Direction)

The stiffness ellipsoid’s direction was computed as:

Results showed:

- Stiffness ellipsoid’s **direction** approximately aligned with the **shoulder-hand axis**

\[ \theta = 56.1° \pm 6.8° \]
Adaptive Impedance Controller

- JOINT ANGLES
- HUMAN ARM DYNAMIC MODEL
- ARM ENDPOINT STIFFNESS ESTIMATION
- USER
- CONTROLLER
- MASTER DEVICE
- REMOTE/VIRTUAL ENVIRONMENT

**Input:**
- Raw EMG
- Raw markers movements

**Processing:**
- Filtered
- Normalized

**Output:**
- PROCESSED EMG
- JOINT ANGLES
- Dynamic Model
- ARM ENDPOINT STIFFNESS

**Control:**
- ADAPTIVE IMPEDANCE CONTROL
Adaptive Impedance Controller – Framework

[Diagram showing the relationship between the user's arm, the master device, and the virtual environment, with dynamic model, stiffness estimation, adaptive damping modulation, and visco-elastic modulation.]

Andrea Passoni
andrea3.passoni@mail.polimi.it
Two implementations of the adaptive impedance controller

1 ENHANCING

- Maximal damping coefficient
- Maximal damping along the direction of maximal stiffness
- It enhances the natural stiffness control strategy
- More isotropic workspace for the human hand
- It simulates an increase in the overall arm impedance

2 ISOTROPIC

- Maximal damping coefficient
- Maximal damping along the perpendicular to the stiffness main axis
- It simulates an increase in the overall arm impedance
One of the modulation strategies for $c_{\text{min}}$ and $c_{\text{max}}$ as a function of the distance $d$ from the target position is the **Low-eccentricity damping field**:

- **Constant in the first phase of the task**

The other modulation strategy is the **Stiffness modulation**:

- Small difference between $c_{\text{min}}$ and $c_{\text{max}}$
- Linearly increasing in the second phase

The equations for the two modulation strategies are:

1. **Low-eccentricity damping field**:
   
   $$c_{\text{min}} / c_{\text{max}}(d) = \rho - c_{\text{min}} / c_{\text{max}}, \quad d \leq \frac{L_T}{2}$$
   
   $$d > \frac{L_T}{2}$$

2. **Stiffness modulation**:
   
   $$K_{\text{max}} = 170, \quad \rho = 0.887, \quad \rho = 0.0003$$
Two modulation strategies for $c_{\text{min}}$ and $c_{\text{max}}$ as function of the distance $d$ from the target position

- **Increased-eccentricity damping field**
  - Constant in the first phase of the task and no damping in the minimal component
  - Linearly increasing in the second phase

$\begin{align*}
c_{\text{min},f}(d) &= \left\{ \begin{array}{ll}
c_{\text{min}/\text{max},0} & \text{for } d \leq \frac{L_T}{2} \\
(c_{\text{min}/\text{max},f} - c_{\text{min}/\text{max},0}) \cdot \frac{d(t)}{L_T/2} & \text{for } d > \frac{L_T}{2}
\end{array} \right.
\end{align*}$

$\begin{align*}
c_{\text{max},f}(d) &= c_{\text{max},0} + (c_{\text{max},f} - c_{\text{max},0}) \cdot \frac{d(t)}{L_T/2}
\end{align*}$
Adaptive Impedance Controller – Damping Modulation Strategies

Low-Eccentricity Damping Fields

Increased-Eccentricity Damping Fields

\[ L_T/2 \]

\[ c_{\text{max}} \]

\[ c_{\text{min}} \]
Testing of the controller – Hypothesis

1. The adaptive impedance controller leads to better performances compared to the constant damping controller.

2. The direction (parallel or perpendicular to the stiffness main axis) along which the damping field is applied affects users’ performances.

There’s an adaptive control strategy that performs better than the other.
Testing of the controller – Acquisition Protocol

First group

- 12 right-handed subjects
- 10 trials of the reaching task for each force condition
- Random order

Second group

- 8 right-handed subjects
- 10 trials of the reaching task for each force condition
- Random order

Null Damping
Enhancing Damping
Isotropic Damping

Null Damping
Improved Enhancing Damping
Improved Isotropic Damping

First session
Random order
Testing of the controller – Performance Metrics

<table>
<thead>
<tr>
<th>$E_{\text{max}}$</th>
<th>$E_{\text{int}}$</th>
<th>$E_{\text{u}}$</th>
<th>$t_{\text{R}}$</th>
<th>$\text{NTL}$</th>
<th>$O$</th>
</tr>
</thead>
</table>

### Performance Metrics

- **Maximal Error ($E_{\text{max}}$)**
  - Maximal distance from the $i^{\text{th}}$ target during the targeting phase.

- **Integral Error ($E_{\text{int}}$)**
  - Integral of the distances from the $i^{\text{th}}$ target normalized by the duration of the targeting phase. It is equal to 0 if the user moves exactly along the Euclidean distance which separates the central position from the target.

- **Unacceptable Error ($E_{\text{u}}$)**
  - Computed as for $E_{\text{int}}$, but considering only the distances higher than the external radius of the target.

- **Reaching Time ($t_{\text{R}}$)**
  - Time needed to reach the $i^{\text{th}}$ target from the central home position.

- **Normalized Travelled Length ($\text{NTL}$)**
  - Normalized length of the path travelled during the reaching phase.

- **Overshoots ($O$)**
  - Number of times that the user goes out from the $i^{\text{th}}$ target.

Diagram:

- Overshoots are marked with an 'Overshoot!' label.
- The maximal error is indicated by a red arrow labeled $E_{\text{max}}$.

Andrea Passoni
andrea3.passoni@mail.polimi.it
### Results – Low-Eccentricity Damping Fields

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<th>$E_{\text{max}}$</th>
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<th>O</th>
</tr>
</thead>
</table>

#### Normalized Travelled Length

![Box plot of normalized travelled length](image)

- Null
- Enhancing
- Isotropic

#### Reaching Time

![Box plot of reaching time](image)

- Null
- Enhancing
- Isotropic

One-way ANOVA, $\alpha = 0.05$

* $p \leq 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$
Results Analysis – Low-Eccentricity Damping Fields

Low-eccentricity damping fields

Users benefit from the introduction of the adaptive impedance controller: improvements in terms of maximal displacement ($E_{\text{max}}$) from the task goal, in the integral error metrics ($E_{\text{int}}, E_u$) and in the mean number of overshoots ($O$).

No difference between the two implementations (Enhancing and Isotropic)

The adaptive impedance controller leads to better performances compared to the constant damping controller.

Increased precision and accuracy with which the teleoperation task is executed.
Results – Increased-Eccentricity Damping Fields

Generalized mixed linear model ($\alpha = 0.05$) (Three-way ANOVA with random effect)

Friedman test ($\alpha = 0.05$)
Results – Increased-Eccentricity Damping Fields

Generalized mixed linear model ($\alpha = 0.05$) (Three-way ANOVA with random effect)
**Results Analysis – Increased-Eccentricity Damping Fields**

**Increased-eccentricity damping fields**

The **Enhancing controller leads to significantly better performance** compared to the Isotropic in terms of both the integral error metrics ($E_{int}$ and $E_u$).

By excluding the $4^{th}$ direction, the **Enhancing performs better also in terms of** maximal displacement from the target’s centre ($E_{max}$).

**Hp 2**

The direction (parallel or perpendicular to the stiffness main axis) along which the damping field is applied affects users’ performances.

By increasing the eccentricity of the damping fields, the **Enhancing controller performs better than the Isotropic one**.
Conclusions – Limitations & Future Work

- **Non disruptive method for** the arm endpoint **stiffness estimation**
- **Novel adaptive impedance controller** which modulates the master device’s damping coefficients reflecting the user’s arm stiffness modulation
- **Potential benefits the biomimetic impedance controller can introduce** in terms of execution accuracy

- Offline stiffness estimation method
- Simple stiffness modulation strategies
- Sigma haptic device not used in the surgical practice

- Real-time estimation to account for users’ dynamic variability
- More complex, 3D tasks
- Adaptive impedance control on the Da Vinci’s console
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