Arm Admittance
experimental approach
Wb2407 Lecture 8

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  • Causality: force vs position perturbations
• Experiment design
  • Perturbations, tasks, environment
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  • Physical model parameterization
• Case studies
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  • II: Shoulder visco-elasticity and reflexes

System descriptions
causality

Only forces \((F)\) can excite a system!

\(\downarrow\)

(Bio-)mechanical systems respond by a corresponding motion \((X)\)

as a consequence: a mechanical system is properly described by its admittance \((= X/F)\)

Force is the driving source

Motion of Mass

\[
\begin{align*}
F &\rightarrow M^{-1}s^{-2} \rightarrow X \\
X &\rightarrow M^{-1}s^{-2} \rightarrow F
\end{align*}
\]

Impedance

\[
\frac{F}{X} = \frac{C}{1 + CM^{-1}s^{-2}} = Ms^2
\]

Biomechanical Forces

External
Voluntary muscle contraction (forward control)
Intrinsic muscle visco-elasticity (feedback control)

Force
Limb
Inertia

Position Perturbations

\[
\begin{align*}
X_{ref} &\rightarrow F_{voluntary} \\
F_{external} &\rightarrow F_{external} \\
\cdots &\rightarrow \infty \\
F_{reflective} &\rightarrow F_{reflective}
\end{align*}
\]

\[
\begin{align*}
M^{-1}s^{-2} &\rightarrow \cdots \\
B_jK &\rightarrow \cdots \\
X_{ref} &\rightarrow \cdots
\end{align*}
\]
Intrinsic, reflexive and voluntary forces can be present (and measured) but have no influence on the motion.

Conclusions
- Force and position are decoupled by the position servo: no mechanical interaction
- Open loop identification techniques can be used

Perturbations, Tasks and Applications

Force perturbations:
• identification of all force contributing mechanisms
  intrinsic + reflexive feedback

Motion Control behaviour

Tasks
• Force task
  – humans generate the appropriate muscle forces to obtain a desired contact force (or pressure) during posture maintenance or while moving
  – human motion control is represented as a mechanical impedance
• Position task
  – humans generate the appropriate muscle forces to obtain a desired motion (tracking) or maintain a posture (disturbance rejection)
  – human motion control is appropriately presented as a mechanical admittance

General:
- position perturbations → 'do not intervene' and/or 'maintain force level'
- force perturbations → 'intervene' to obtain certain motions or maintain a posture

+ integrity tests
+ not functional to study neuromuscular control properties
+ functional assessment
Perturbations, Tasks and Applications

Applications

<table>
<thead>
<tr>
<th>Perturbation</th>
<th>Position</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>useless</td>
<td>• intervene on position</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• what is the role of force feedback?</td>
</tr>
<tr>
<td>Force</td>
<td>• intervene on force</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• force feedback useful (Golgi tendon organs)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• what is the role of muscle spindles?</td>
<td></td>
</tr>
</tbody>
</table>

Combination of task and perturbation is determined by the experimental objective.

Perturbations, Tasks and Applications

common applications

<table>
<thead>
<tr>
<th>Task dependent muscle activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexor EMG</td>
</tr>
<tr>
<td>Exensor EMG</td>
</tr>
<tr>
<td>Force</td>
</tr>
<tr>
<td>Position</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>90</td>
</tr>
<tr>
<td>100</td>
</tr>
<tr>
<td>Time (ms)</td>
</tr>
</tbody>
</table>

(Doemges and Rack, 1992)

Perturbations

Force perturbations: predictable or unpredictable?

Predictable:

• humans tend to generate voluntary actions

Unpredictable:

• humans can not anticipate to the perturbation
• effective control only by intrinsic and/or reflexive feedback only

Perturbations

Force perturbations: continuous or transient?

Transients:

• be at the mercy of the perturbation
  stability and performance not relevant to the perturbation

Continuous:

• adaptation / interaction to the mechanical environment
  stability and performance are relevant task properties

Time or Frequency domain?

Time domain:

• transient signals
• signal analyses easy by eye
• system dynamics hard to retrieve
• general applications

Frequency domain:

• continuous signals
• system dynamics can easily be visualized
• only for linear time invariant (LTI) systems

Endpoint vs Joint measurement

Multiple DOFs (linearized):

• Endpoint translation:
  \[ F = Ms^2 + Bs + K \]
  \[ X = \frac{1}{Ms^2 + Bs + K} \]

• Joint rotation:
  \[ \theta = \frac{1}{Is^2 + B_s + K_o} \]
Transformation from joint to end-point coordinates.

2 DOF example (non redundant):

\[
\begin{align*}
x &= l \cos(\theta) + l_1 \cos(\theta_1 + \theta_2) \\
y &= l \sin(\theta) + l_1 \sin(\theta_1 + \theta_2) \\
dx &= -l_1 \sin(\theta_1 + \theta_2) (\theta_1 + \theta_2) \\
dy &= l_1 \cos(\theta_1 + \theta_2) (\theta_1 + \theta_2)
\end{align*}
\]

\[
\begin{bmatrix}
x' \\
y'
\end{bmatrix} =
\begin{bmatrix}
-l_1 \sin(\theta_1 + \theta_2) & -l_1 \sin(\theta_1 + \theta_2) \\
l_1 \cos(\theta_1 + \theta_2) & l_1 \cos(\theta_1 + \theta_2)
\end{bmatrix}
\begin{bmatrix}
\theta_1' \\
\theta_2'
\end{bmatrix}
\]

The redundant case: Jacobian is not square and can not be inverted (DOF \( q_\text{r} > \text{DOF}_x \)). Consequently, the joint admittance can not uniquely be derived from the measured endpoint admittance.

System Description

Different system descriptions:
- differential equations (equations of motion)
- state space equations
- impulse response functions (IRF)
- frequency response functions (FRF)

Nonlinear:
- chain of linear subsystems?
- sophisticated techniques

Linear approach:
- Fourier, Bode, Nyquist
- performance & stability analysis
  (pole-zero analyses)

Posture Control at DUT

Objective: Posture maintenance
small deviations of state variables \(\Rightarrow\) linear approach justified

Hypotheses: all force contributing mechanisms (intrinsic and reflexive) are functional to the task

Goal: Quantification of reflexive feedback

Perturbations: Force perturbations
Task instruction: Minimize position deviations

Case study

Admittance Decomposition from Force Perturbations (Shoulder)

Task instruction: "Minimize position deviations":

\[
\text{Goal: "Minimize arm admittance"}
\]

\[
J_k = \sum_{i=1}^{n_k} X(t) \frac{df}{dt} = \sum_{i=1}^{n_harm} \text{Harm}(\frac{f}{t}) \frac{df}{dt} = C \sum_{i=1}^{n_harm} \text{Harm}(\frac{f}{t}) \frac{df}{dt}
\]
Measurement Scheme
posture control, force perturbation

\[ X_{\text{ref}} = 0 \]

Closed-loop system identification:
- estimate \( H_{\text{arm}} \) from measured signals

Hypotheses
Hypotheses: all force contributing mechanisms (intrinsic and reflexive) are relevant to the task

Intrinsic properties
Effect of intrinsic stiffness and damping \( B_{\text{int}}, K_{\text{int}} \):

Reflexive feedback
Effect of reflexive stiffness and damping \( K_p, K_v \):

1DOF Shoulder Admittance
- linear movement of the hand
- continuous random force perturbations, position task

Measured 1DOF Signals
Data Processing

For estimating the transfer function $H_{arm}(f)$, an independent signal is needed from outside the loop.\[\hat{H}_{arm}(f) = \frac{G_{y}(f)}{G_{u}(f)}\]

An estimation of $H_{arm}(f)$, i.e. $\hat{H}_{arm}(f)$, can be retrieved from spectral densities:
\[
H(\hat{f}) = \frac{\hat{G}_{y}(\hat{f})}{\hat{G}_{u}(\hat{f})}\]

See De Vlugt 2002 and college 'System Identification' for details.

Data Processing

Time signals are directly transformed to the frequency domain by the Fast Fourier Transform (FFT):
\[
y(t) \rightarrow Y(f)\]

Spectral densities:
\[
\hat{G}_{y}(f) = Y(f)Z(-f)\]
\[
\hat{G}_{u}(f) = \hat{Y}(f)\hat{Y}(-f) = |Y(f)|^2\]

Results

Estimated transfer functions $H_{arm}(f)$ of the arm for different environments:

<table>
<thead>
<tr>
<th>$M_e$ [kg]</th>
<th>$B_e$ [Ns/m]</th>
<th>$H_{arm}(f)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>142</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>344</td>
<td></td>
</tr>
</tbody>
</table>

Frequency [Hz]

Results

Estimated transfer functions of total system (arm+environment):

<table>
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<th>$M_e$ [kg]</th>
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</tbody>
</table>

Frequency [Hz]
Results
Estimated reflex gains $K_p$ and $K_v$:

\[
\begin{align*}
M_x &= 0.8 \text{ kg} \\
M_x &= 5.0 \text{ kg} \\
M_x &= 10.0 \text{ kg}
\end{align*}
\]

Control effort (CE) weighting:

\[
\sum_{x} \gamma_x = \frac{1}{\gamma_x} \int \gamma_x \left( \gamma_x \cdot \left( F_r - F_r \right) \right) \, dx
\]

with $H(x)$ (in this case) the FRF from $D \rightarrow F_{ref}$

Note: intrinsic parameters were fixed at their estimated values.

Optimized Reflex Gains

Optimized Length Feedback

- Only length feedback
- One CE weighting factor

2DOF Shoulder Admittance

- 2 dof measurements at hand level
- 3 dof identification on joint level
- A redundancy problem

2DOF Shoulder Admittance

- 2 dof measurements at hand level
- 3 dof identification on joint level
- A redundancy problem
- Unique solution possible due to realistic model including only mono- and biarticulate coupling
Conclusions Case study

- Monosynaptic reflex gains $K_p$ and $K_v$ vary with increasing damping and mass of the environment
- These reflex gains can be explained analytically using common control engineering techniques
- Model optimizations can determine whether the adjustments are optimal
- The combination force perturbations – position task is very appropriate to obtain knowledge of the controllability of the central nervous system during natural movements