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Minimally Invasive Surgery (MIS)

MIS (laparoscopy) advantages with respect to open surgery:

• Less trauma for patient ✓
• Shorter recovery time ✓

• More difficulties for the surgeon ✗
  - Upright position: fatigue
  - No hand–eye coordination
  - 2D perception
  - Fulcrum effect
  - No hand palpation
Minimally Invasive Surgery

Improvements of robot-assisted MIS:

- Filtered hand tremor ✓
- Scaling of movements ✓
- Surgeon comfort and immersion ✓

- Separation between patient and surgeon: no feeling of the applied force ✗

A haptic feedback is desirable for:
- Lump detection
- Suture knots
On board sensors are costly, cumbersome and need to be sterilizable

A sensorless strategy is to reconstruct the interaction wrench from the joint torques, which can be estimated from the currents in the motors (Sang, 2017).

The dynamics of the slave arm must be considered

b) Fontanelli, et al., IROS, IEEE 2017
d) Seibold, et al. ICRA. IEEE, 2005
To estimate the interaction wrench from the joint torques, **taking into account the dynamics**

- The **dynamic model** of the dVRK slave arm must be modeled
- The **parameters** of the model must be defined and identified
dVRK Hardware

Open version of the da Vinci System

Intended for research only

- 2 Master Tool Manipulators (MTM)
- 2 Patient Side Manipulators (PSM)
- High resolution stereo viewer (HRSV)
- Footpedal
The total torque sensed at the joint level consists of:

- **dynamic torques** $\hat{\tau}$, causing the robot motion
- $\tau_{EXT}$: Torques resisting to an external interaction wrench
Dynamic Model

The total torque sensed at the joint level consists of:

- **dynamic torques** \( \hat{\tau} \), causing the robot motion
- **\( \tau_{EXT} \)**: Torques resisting to an external interaction wrench

 Joint positions \( q \)
Joint velocities \( \dot{q} \)
Joint accelerations \( \ddot{q} \)

\( w = [F_x, F_y, F_z, T_x, T_y, T_z] \)

Interaction Wrench

\( J^T \)

\( \hat{\tau}, \tau_{TOT}, \tau_{EXT} \)
Dynamic Model

\[ \dot{\tau} = M(q)\ddot{q} + C(q, \dot{q}) + G(q) + K_e q + F_v \dot{q} + F_s \text{sgn}(\dot{q}) + \tau_0 + I_a \ddot{q} \]

- **Inertia Matrix**
- **Coriolis & centrifugal forces matrix**
- **Simplified drive inertia**
- **Static friction offset**
- **Static – Coulomb friction**
- **Viscous friction**
- **Joint elasticity, due to power cables and a torsional spring**

**Constants**:

- \( I_a = \text{diag}\{I_{a1}, \ldots, I_{a6}\} \)
- \( \tau_0 \) static friction offset
- \( F_s = \text{diag}\{F_{s1}, \ldots, F_{s6}\} \)
- \( F_v = \text{diag}\{F_{v1}, \ldots, F_{v4}, F_{vl}\} \)
- \( K_e = \text{diag}\{K_{e1}, K_{e2}, 0, K_{e4}, 0, 0\} \)
Dynamic Model

The model is linear w.r.t the vector $\delta$ of the dynamic parameters:

Expressions of $Y$ and $\delta$ are computed using the **Newton Euler Algorithm**

$$\tau = Y(q, \dot{q}, \ddot{q}) \ast \delta$$
The **Newton Euler Algorithm** computes the dynamic model taking as input the robot DH parameters.

The DH parameters \(a, \alpha, d, \theta\), define univocally, for every degree of freedom, the kinematics of the robot arm.
While the robot is performing the optimal trajectory, $q, \dot{q}, \ddot{q}, \tau$ are collected, at a frequency of 100 Hz.
Identification

While the robot is performing the optimal trajectory, $q, \dot{q}, \ddot{q}, \tau$ are collected.

$$
\begin{bmatrix}
Y(q_1, \dot{q}_1, \ddot{q}_1) \\
\vdots \\
Y(q_M, \dot{q}_M, \ddot{q}_M)
\end{bmatrix} \delta = 
\begin{bmatrix}
\tau_1 \\
\vdots \\
\tau_M
\end{bmatrix}
$$

$M = n^\circ$ of samples

The optimal parameter $\delta^*$ vector is obtained by pseudoinversion of $Y$, solving a least squares minimization problem.
Identification

\[
\begin{bmatrix}
Y(q(t_1), \dot{q}(t_1), \ddot{q}(t_1)) \\
\vdots \\
Y(q(t_M), \dot{q}(t_M), \ddot{q}(t_M))
\end{bmatrix}
\delta =
\begin{bmatrix}
\tau(t_1) \\
\vdots \\
\tau(t_M)
\end{bmatrix}
\]

1) Data Collection

\[W = \text{diag}\left\{ \frac{1}{\tau_{1,\text{max}}}, \ldots, \frac{1}{\tau_{6,\text{max}}} \right\}\]

2) Weighting Matrix Definition

\[\delta^* = \left[ W \ast Y(q(t_1), \dot{q}(t_1), \ddot{q}(t_2)) \right]^+ \ast \left[ W \ast \tau(t_1) \right] \]

3) Parameter Identification, by pseudo inversion of weighed matrices
Validation of the Dynamic Model

Validation is done by estimating joint torques in a free space motion.

Ideally, the estimated torques are equal to the sensed torques.

\[ \hat{\tau} = Y(q, \dot{q}, \ddot{q}) \times \delta^* \]

\[ NRMSD_i = \frac{1}{N} \sqrt{\sum_{n=1}^{N} \left[ \hat{\tau}_n - \tau_n \right]^2} \]

- \( N \) number of samples
- \( i \) joint number
- \( \tau_{max} \) maximum torque over time
- \( \tau_{min} \) minimum torque over time
Wrench Estimation Method

In case of an interaction wrench:

$$\tau_{ext} = \tau_{TOT} - \hat{\tau}$$

The external wrench can be calculated as:

$$\bm{w} = (J^T)^{-1} \ast \tau_{ext}$$
## Validation

<table>
<thead>
<tr>
<th>joints</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRMSD(%)</td>
<td>2.38</td>
<td>4.80</td>
<td>12.83</td>
<td>6.49</td>
<td>15.29</td>
<td>18.11</td>
</tr>
</tbody>
</table>

$$NRMSD_i = \frac{1}{N} \sqrt{\sum_{n}^{N} [\hat{\tau}_n - \tau_n]^2} \frac{(\tau_{max} - \tau_{min})_i}{(\tau_{max} - \tau_{min})_i}$$

Francesco Piqué, Thesis Discussion
Wrench Estimation Results

<table>
<thead>
<tr>
<th></th>
<th>Fx</th>
<th>Fy</th>
<th>Fz</th>
<th>Tx</th>
<th>Ty</th>
<th>Tz</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRMSD(%)</td>
<td>8.26</td>
<td>5.96</td>
<td>6.10</td>
<td>8.13</td>
<td>5.71</td>
<td>15.50</td>
</tr>
</tbody>
</table>

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Conclusions

A model of the PSM arm was implemented and its parameters were identified.

The model was validated by evaluating its torque estimation ability at the joint level and the interaction wrench estimation ability.

Future work may include the reflection of the estimated forces to the master side.
Thanks for your attention!
The optimal excitation trajectory was computed **offline**, from the equation:

\[ q_i(t) = \sum_{l=1}^{L} \frac{a_i^l}{\omega_f l} \sin(\omega_f l t) - \frac{b_i^l}{\omega_f l} \cos(\omega_f l t) + q_{i0} \]

\[ L = 5 \text{ Number of harmonics} \]
\[ \omega_f = 2\pi \times 0.1 \text{ rad/s fundamental frequency} \]
\[ i \text{ joint number} \]

Parameters \( a_i^l, b_i^l, q_{i0} \) are tuned to minimize the conditioning number of:

\[
\begin{bmatrix}
  Y(q_1, \dot{q}_1, \ddot{q}_1) \\
  \vdots \\
  Y(q_M, \dot{q}_M, \ddot{q}_M)
\end{bmatrix}
\]
### Dynamic Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{v6}$</td>
<td>0.0087</td>
</tr>
<tr>
<td>$f_{v5}$</td>
<td>0.015</td>
</tr>
<tr>
<td>$K_{x1}$</td>
<td>2.5958</td>
</tr>
<tr>
<td>$K_{x2}$</td>
<td>0.6219</td>
</tr>
<tr>
<td>$K_{x4}$</td>
<td>0.0022</td>
</tr>
<tr>
<td>$m_3$</td>
<td>0.0115</td>
</tr>
<tr>
<td>$l_x1$</td>
<td>0.2298</td>
</tr>
<tr>
<td>$l_1y + l_2z$</td>
<td>-0.0069</td>
</tr>
<tr>
<td>$f_{e1}$</td>
<td>0.1090</td>
</tr>
<tr>
<td>$f_{e3}$</td>
<td>0.1363</td>
</tr>
<tr>
<td>$\tau_{e1}$</td>
<td>-0.3259</td>
</tr>
<tr>
<td>$l_x2$</td>
<td>-0.0013</td>
</tr>
<tr>
<td>$l_y2$</td>
<td>-0.2103</td>
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<tr>
<td>$f_{e2}$</td>
<td>0.2940</td>
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<tr>
<td>$f_{e3}$</td>
<td>1.7079</td>
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<tr>
<td>$\tau_{e3}$</td>
<td>0.4847</td>
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<tr>
<td>$l_x4$</td>
<td>7.74e-4</td>
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<tr>
<td>$l_y4 + l_y5$</td>
<td>-2.77e-4</td>
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<tr>
<td>$I_{a4}$</td>
<td>-9.86e-5</td>
</tr>
<tr>
<td>$f_{e4}$</td>
<td>0.0015</td>
</tr>
<tr>
<td>$f_{e3}$</td>
<td>0.0029</td>
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</table>

<table>
<thead>
<tr>
<th>Equation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{a1} + L_{z1} + L_{y2} + L_{z3}$</td>
<td>0.0201</td>
</tr>
<tr>
<td>$L_{xx2} - L_{yy2} + L_{xx3} - L_{zz3} + 0.8324 \times l_z4$</td>
<td>0.0385</td>
</tr>
<tr>
<td>$L_{xy2} - L_{xz3}$</td>
<td>-0.0352</td>
</tr>
<tr>
<td>$L_{xz2} - L_{xy3}$</td>
<td>-0.0072</td>
</tr>
<tr>
<td>$L_{yz2} - L_{xz3}$</td>
<td>0.0012</td>
</tr>
<tr>
<td>$I_{a2} + L_{zz2} + L_{yy3} + 0.8324 \times l_z4$</td>
<td>-6.32e-4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{e4}$</td>
<td>-0.0052</td>
</tr>
<tr>
<td>$l_{x5}$</td>
<td>2.9e-5</td>
</tr>
<tr>
<td>$l_{y5}$</td>
<td>5.83e-4</td>
</tr>
<tr>
<td>$I_{a5}$</td>
<td>-0.0025</td>
</tr>
<tr>
<td>$f_{v5}$</td>
<td>0.0271</td>
</tr>
<tr>
<td>$f_{e5}$</td>
<td>0.0126</td>
</tr>
<tr>
<td>$l_{x6}$</td>
<td>2.59e-4</td>
</tr>
<tr>
<td>$l_{y6}$</td>
<td>1.52e-4</td>
</tr>
<tr>
<td>$l_{z6}$</td>
<td>-0.0014</td>
</tr>
<tr>
<td>$I_{a6}$</td>
<td>-0.0028</td>
</tr>
<tr>
<td>$f_{e6}$</td>
<td>0.014</td>
</tr>
<tr>
<td>$f_{e6}$</td>
<td>0.004</td>
</tr>
</tbody>
</table>

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### Identification

- **Data Collection**
- Sampling Rate 100 Hz
- Butterworth 3rd order LPF at 10 Hz

- **One for each time sample**

- **Weighting matrix**

  \[ W_k = \text{diag}\left\{ \frac{1}{\max(\tau_1)}, \ldots, \frac{1}{\max(\tau_6)} \right\} \]

- **Weight the equations**

  \[
  A_w = \begin{bmatrix}
  W_1 * Y(q_1, \dot{q}_1, \ddot{q}_1) \\
  \vdots \\
  W_M * Y(q_M, \dot{q}_M, \ddot{q}_M)
  \end{bmatrix}, \quad
  b_w = \begin{bmatrix}
  W_1 * \tau_1 \\
  \vdots \\
  W_M * \tau_M
  \end{bmatrix}
  \]

- **Linear least squares solution**

  \[
  \delta^* = A_w^+ * b_w
  \]

Recall the model’s equation:

\[ \tau = Y(q, \dot{q}, \ddot{q}) \delta \]