Chapter 4: controlling robots in contact with their environment

Guillaume Morel
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Why?

• So far we’ve seen how to position a robot from either proprioceptive sensors (conventional robot position control from joint sensors with registration) or exteroceptive sensors (visual servoing).

• When a contact is to be established with the environment, forces appear. The resolution of a position sensor is insufficient to master forces (if the stiffness is high).

• Force control consists in controlling the force applied by a robot rather than the position.
Force Transmission

Joint forces/torques $\gamma$  
Operational forces $f$

Static model
Inverse static model
Wrenches between two rigid bodies

\[ m^{A}_{1\rightarrow 2} = m^{B}_{1\rightarrow 2} + f_{1\rightarrow 2} \times t_{BA} \]

Mechanical Power:

\[ \mathbf{p} = m^{A}_{1\rightarrow 2} \cdot \boldsymbol{\omega}_{2/1} + v^{A}_{2/1} \cdot f_{1\rightarrow 2} \]
Perfect links

\[ \mathbf{p} = m_{1 \rightarrow 2}^A \mathbf{\omega}_{2/1} + v_{2/1}^A \cdot f_{1 \rightarrow 2} = 0 \]

Example: For a rotational joint between body \(i-1\) and body \(i\), we have seen that, in \(\mathbb{R}_{\mathbf{b}_i}\):

\[
\begin{pmatrix}
    i \omega_{i/i-1} \\
    i \theta_{i} \\
    i \nu_{i/i-1}
\end{pmatrix} = \begin{pmatrix} 0 & 0 & \dot{\theta}_i & 0 & 0 & 0 \end{pmatrix}^T.
\]

Then we have:

\[
\begin{pmatrix}
    i m_{i-1 \rightarrow i}^O \\
    i f_{i-1 \rightarrow i}
\end{pmatrix} = \begin{pmatrix} m_x & m_y & 0 & f_x & f_y & f_z \end{pmatrix}^T.
\]

To generate a torque around \(k_i\), we will thus need to use an actuator.
Computation

Considering a robot with \( n \) joints, with a velocity transmission model:

\[
\begin{pmatrix}
0 \\
0 \\
\omega_{n/0}
\end{pmatrix} = \mathbf{J}_{NM}(q) \dot{q}
\]

At the joint level, the mechanical power writes:

\[
\mathbf{p}_{\text{articulaire}} = \gamma^T \dot{q}
\]

Suppose now that a wrench is applied directly to the end \( 0 \rightarrow n \), the mechanical power that it produces is:

\[
\mathbf{p}_{\text{opérationnelle}} = m_{0\rightarrow n}^M \cdot \omega_{n/0} + v_{n/0}^M \cdot f_{0\rightarrow n} = \begin{pmatrix}
m_{0\rightarrow n}^M \\
f_{0\rightarrow n}
\end{pmatrix}^T \begin{pmatrix}
\omega_{n/0} \\
v_{n/0}^M
\end{pmatrix}
\]

The two force systems \( \gamma \) and \( \begin{pmatrix}
m_{0\rightarrow n}^M \\
f_{0\rightarrow n}
\end{pmatrix} \) are said to be equivalent if and only if they produce the same power whatever the velocity, \( i.e. \):

\[
\begin{pmatrix}
m_{0\rightarrow n}^M \\
f_{0\rightarrow n}
\end{pmatrix}^T \begin{pmatrix}
\omega_{n/0} \\
v_{n/0}^M
\end{pmatrix} = \begin{pmatrix}
m_{0\rightarrow n}^M \\
f_{0\rightarrow n}
\end{pmatrix}^T \mathbf{J}_{NM}(q) \dot{q} = \gamma^T \dot{q}, \quad \forall \dot{q}
\]

Thus:

\[
\begin{pmatrix}
m_{0\rightarrow n}^M \\
f_{0\rightarrow n}
\end{pmatrix}^T \mathbf{J}_{NM}(q) = \gamma^T, \quad \text{or:} \quad \gamma = \mathbf{J}_{NM}^T(q) \begin{pmatrix}
m_{0\rightarrow n}^M \\
f_{0\rightarrow n}
\end{pmatrix}
\]

Thus:

\[
\mathbf{J}_{NM}(q) = \gamma^T, \quad \text{or:} \quad \gamma = \mathbf{J}_{NM}^T(q) \begin{pmatrix}
m_{0\rightarrow n}^M \\
f_{0\rightarrow n}
\end{pmatrix}
\]
Controlling a robot in contact with its environment

• Explicit force control:
  – Open loop
  – With inner position loop
  – Direct force control

• Impedance control
How to control forces?

1: open-loop

• One exploits the static model:

\[ \gamma = J^T_{NM}(q) \begin{pmatrix} m^M_0 \to n \\ f^I_0 \to n \end{pmatrix} \]

• Problems:
  – Inertia of the moving bodies
  – Friction at transmission elements

⇒ The actuator torque is not the net output torque.
Reducing inertia

• Reducing inertia:
  – Compactness (optimize size vs workspace)
  – Light material (inertia vs rigidity)
  – Optimize transmission ratio
    • High gear ratio allows to exert large forces from small actuators.
    • But they dramatically increase output inertia. Indeed :
      – If motor inertia = $I_m$ and gear ratio = $N$.
      – Then Output inertia = $N^2 I_m$
  – Minimize coupling (search for isotropy)
Low friction robot design

- Low gear ratio preferable
- Cable transmission ++ (low friction + motors close from the robot base)
- Reduce hyperstaticity.
- Example 1: cable differential (drawings from patent US 5,207,114; used in WAM => Makoplasty)

Low friction robot design

– Example 2: screw cable technology
Compensation for mechanical effects

• Exploit models to compute compensation torques from position/velocity/acceleration measurement.
  – Gravity compensation: somewhat easy and inexpensive
  – Model based Friction compensation: difficult & somewhat inefficient
  – Inertia compensation: may help – acceleration sensors required
Force control with an internal loop

Desired end-effector position

Trajectory correction = admittance

Computation of the joint position error

Joint position compensator

Joint torque input

Robot dynamics

Joint position output

Force sensor

Desired Force = 0

Interaction dynamics

End-effector position

Direct kinematics

Environment position

Force
Main limitation: lightweight robot = high feedback gains = instability

1st approximation:

\[ m^* \geq \frac{1}{2} m_{\text{robot}} \]

[Dohring 03] minimum passive inertia achievable

M. Dohring and W. Newman, “The passivity of natural admittance control implementations, ICRA 03
Example: Dermarob
Control law

Trajectory generation

Learning Situations $X_{ini}^0$ and $X_{fin}^0$

Frame transfor. $R_E \rightarrow R_0$

IGM with test of singularity

Joint PID

Robot

Resolvers

Force sensor

Desired Forces $H_d^E$

Selection matrix $S$

Gravity Compensation $H^E_g$

Frame transfor. $R_s \rightarrow R_E$

Credit: E. Dombre – Montpellier.
Video
Result
Achieving high bandwidth tanks to direct force control

Desired force = 0 +

Torque error computation → Torque compensator

Joint torque input → Robot dynamics

Joint position output

Force dynamics

Interaction dynamics

Environment position

End-effector position

Direct kinematics
Example: force control for laparoscopic surgery
Motivations

• Force feedback teleoperation.
• Physiological motion compensation.
• Autonomous assistance:
  – Tension control when suturing.
  – Holding organs during their ablation.
Measuring forces in laparoscopic surgery

- Sensing forces between instrument and organs is required.
- Precise-and-small enough sensors do not exist.
- Wrist sensing leads to a corruption of the measure due to *trocar disturbances*.
A mechatronic solution

\[ F_{\text{measured}} = F_{\text{organ}} + \text{grav.} + \text{dyn.} \]
Prototyping

• 4 DOF spherical kinematics.
• 2 first joints for orienting the trocar around the fulcrum point.
• 2 last joints for relative motion of the instrument w.r.t. the trocar.
• ATI nano43 force sensor in the middle of the kinematic chain.
Force measurement verification
Control problem: selecting the force components

- 4 DOF robot; 6 component wrench measurement $w$.
- No idea where the contact is.
- What error should be servoed?
  - Component selection: $\varepsilon_R = R_{4 \times 6} (w_d - w)$
  - Joint space projection: $\varepsilon_\tau = J^T (w_d - w)$
Formal analysis

- PI compensator:

\[ \tau_c = \tau_d + \left( K_p + \frac{K_i}{s} \right) (\tau_d - \tau_e) := C_\tau(s) \]

- Interaction port admittance:

\[ Y_w(s) = \frac{v}{-w_e} = J Y_r(s) \left[ J^T + C_\tau(s) J^T S \right] \]

- Passivity conditions:

\[
\begin{align*}
\text{a)} & \quad B^{-1} K_i \text{ is PSD.} \\
\text{b)} & \quad M = K_p M K_p^{-1} \\
\text{c)} & \quad (I_n + K_p) B - K_i M \text{ is PSD.} \\
\text{d)} & \quad BK_i = K_i B.
\end{align*}
\]

\[ SJ = J \]
In vivo validation
Ability to maintain contact despite breathing

• Natural disturbance rejection properties
Assistance to surgery

Two successful cholecystectomies realized with pigs by Dr. N. Bonnet at the Surgery School of Paris (APHP).