Modeling and dynamic identification of medical devices : theory, issues and example

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Introduction

- Control and simulation of robot → **accurate dynamic model needed**.

- Usual identification process: ***IDIM-LS* method**:

  → based on **Inverse Dynamic Model** and **Least Squares estimation**,

  → successfully applied on many rigid robots,

  → **needs motor torques and positions** measurement (rigid and flexible dof)

  →velocities and accelerations are calculated from a **band pass filtering** of positions.

Introduction

- Medical devices add some issues over industrial robots :

  medical safety constraints,:

  → quasi-**irreversible gearbox** (case of power failure),

  lightness constraints :

  → **flexible systems**.

Modified Denavit-Hartenberg notation

- Kinematic of robots defined using **Modified Denavit-Hartenberg** (*MDH*) notation

  → **systematic notation** of all robots,

  → **automatic computation** of :

  - geometric, kinematic and dynamic models,
  - **inverse dynamic model linear to parameters,**

with **Symoro+** (+ Mathematica) or **OpenSYMORO** (+ Python, open-source) software (*IRCCyN)*.

Inverse Dynamic Model

- **Inverse Dynamic Model** (*IDM*) → torques **function of** positions $\mathbf{q}$, velocities $\dot{\mathbf{q}}$ and accelerations $\ddot{\mathbf{q}}$

$$\text{motor torques} \left\{ \boldsymbol{\tau}_{\mathrm{mdi\_m}} = \overbrace{\mathbf{Ia}}^{\text{rotor inertias}}\ddot{\mathbf{q}} + \boldsymbol{\tau}_{\mathrm{f}} + \boldsymbol{\tau}_{\mathrm{L}} \right. \quad \text{with}$$

$$\text{joint torques} \left\{ \boldsymbol{\tau}_{\mathrm{L}} = \underbrace{\mathbf{M}(\mathbf{q})}_{\text{bodies inertia matrix}}\ddot{\mathbf{q}} + \overbrace{\mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}}}^{\text{centrifugal and Coriolis torques}} + \underbrace{\mathbf{Q}(\mathbf{q})}_{\text{gravity torques}} \right.$$

$$\text{friction torques} \left\{ \boldsymbol{\tau}_{\mathrm{f}} = \mathbf{Fv}\dot{\mathbf{q}} + \mathbf{Fc}\,\mathrm{sign}(\dot{\mathbf{q}}) \right.$$

All parameters and variables expressed in units on joint side.

Torques linear to parameters

- With ***DHM* notation** :

→ Torques **linear** to **base dynamic parameters** $\boldsymbol{\chi}$ **:**

$$\boldsymbol{\tau}_{\mathrm{mdi\_m}} = \mathbf{Ia}\ddot{\mathbf{q}} + \boldsymbol{\tau}_{\mathrm{f}} + \boldsymbol{\tau}_{\mathrm{mdi\_L}}$$

$$\downarrow$$

$$\boldsymbol{\tau}_{\mathrm{mdi\_m}} = \mathbf{MDI}\left(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}\right)\boldsymbol{\chi}$$

- dynamic parameters $\boldsymbol{\chi}$:
  - inertial parameters (Ia, XX, XZ,..., ZZ)
  - gravity parameters (M, MX, MY, MZ)
  - viscous and Coulomb frictions (Fv et Fc)

Inverse Dynamic Identification Model with Least-Squares

$$\boldsymbol{\tau}_{mdi} = \mathbf{MDI}(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}})\boldsymbol{\chi} \quad \rightarrow \quad \underbrace{\boldsymbol{\tau}_{m}}_{\text{Measured motor torques}} = \mathbf{MDI}(\mathbf{q},\dot{\mathbf{q}},\ddot{\mathbf{q}})\boldsymbol{\chi} + \underbrace{\mathbf{e}}_{\text{noises}}$$

$$\downarrow$$

- sampling
- // filtering and downsampling of **Y** and **W**

➢ overdetermined system: $\mathbf{Y} = \underbrace{\mathbf{W}(\hat{\mathbf{q}},\hat{\dot{\mathbf{q}}},\hat{\ddot{\mathbf{q}}})}_{\text{Observation matrix}}\boldsymbol{\chi} + \boldsymbol{\rho}$

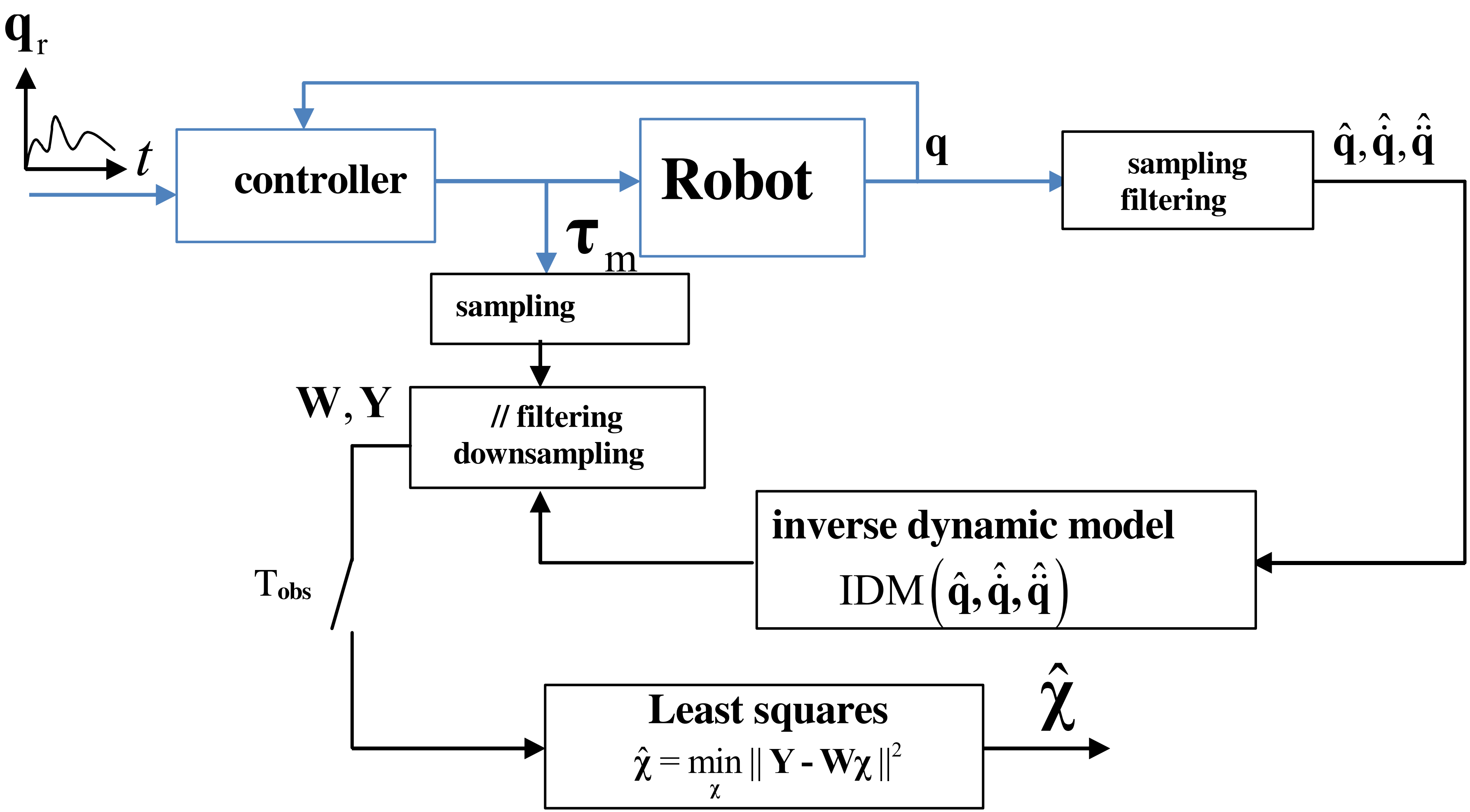
$(\hat{\mathbf{q}},\hat{\dot{\mathbf{q}}},\hat{\ddot{\mathbf{q}}})$ computed by **bandpass filtering** of $\mathbf{q}$

Dynamic parameters estimation

→ $\hat{\chi}$ **least-squares solution** of the overdetermined system $\mathbf{Y} = \mathbf{W}\boldsymbol{\chi} + \boldsymbol{\rho}$

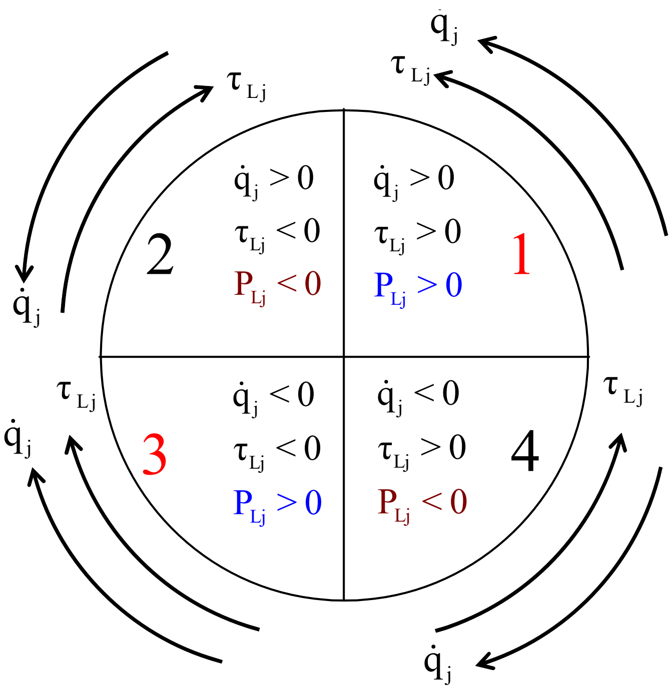
- **weighted** least squares**,**
- computation of **standard relative deviations** (confidence of parameters),
- **model reduction** → keep only a set of essential parameters.

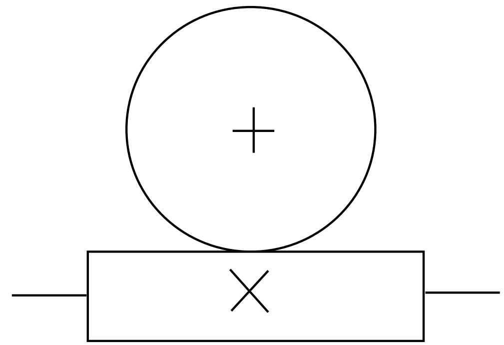
IDIM-LS method



Issue of medical devices

- Use of **quasi-irreversible gearbox**





Motor power : $P_{mj} = \tau_{mj}\dot{q}_j$

$\neq$

Joint power : $P_{Lj} = \tau_{Lj}\dot{q}_j$

Gear efficiency depend on **sign of joint power**

Inverse Dynamic Model

- new **Inverse Dynamic Model** (*IDM*)

$$\boldsymbol{\tau}_{\mathrm{mdi\_m}} = \mathbf{Ia}\ddot{\mathbf{q}} + \boldsymbol{\tau}_{\mathrm{fp}} + \boldsymbol{\tau}_{\mathrm{fn}} + \mathbf{R}\boldsymbol{\tau}_{\mathrm{mdi\_L}}$$

$$\tau_{\mathrm{fpj}} = 0.5\left(1+\mathrm{sign}\left(\dot{q}_j\right)\right)\left(\mathrm{Fcp}_j + \mathrm{Fvp}_j\dot{q}_j\right)$$

$$\tau_{\mathrm{fnj}} = 0.5\left(1-\mathrm{sign}\left(\dot{q}_j\right)\right)\left(\mathrm{Fcn}_j + \mathrm{Fvn}_j\dot{q}_j\right)$$

$$\mathrm{R}_{\mathrm{jj}} = 0.5\left[\left(1+\mathrm{sign}\left(\tau_{\mathrm{Lj}}\dot{q}_j\right)\right)\mathrm{r1}_j + \left(1-\mathrm{sign}\left(\tau_{\mathrm{Lj}}\dot{q}_j\right)\right)\mathrm{r2}_j\right]$$

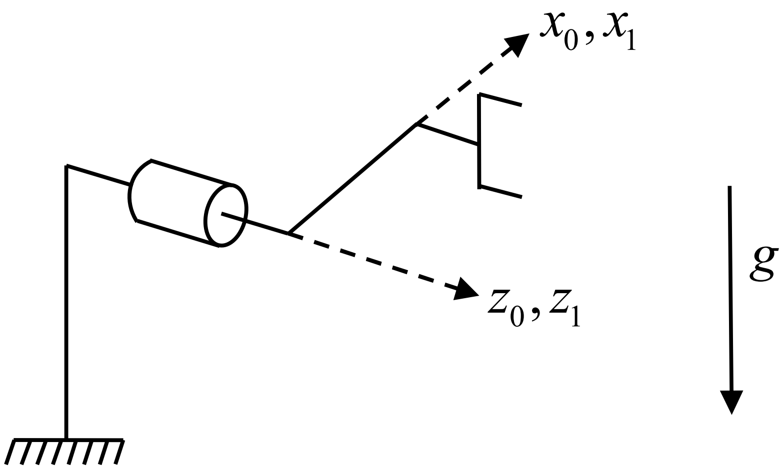
The Discovery IFS 730 of General Electric Healthcare

- **IRIMI** project
  (finish two years ago, now no-confidential)

- **3 degrees of freedom** robot,
  → revolute joint, C-arm and lift,
- used for **capture X-ray 3D image**,
- **mobile** platform

- Interest : **patient can be immobile** for interventional procedure.

Modeling rigid model



Classic inverse dynamic model :

$$\tau_{m1} = ZZ_{1R}\ddot{q}_1 - MX_1 g\cos(q_1) + \ldots$$
$$+ MY_1 g\sin(q_1) + Fv_1\dot{q}_1 + Fc_1\mathrm{sign}(\dot{q}_1)$$

$$ZZ_{1R} = ZZ_1 + Ia_1$$

Inverse dynamic model linear to parameters:

$$\boldsymbol{\tau}_m = \mathbf{IDM}\left(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}\right)\boldsymbol{\chi} + \mathbf{e}$$

with

$$\begin{cases} \boldsymbol{\tau}_m = \tau_{m1} \\ \mathbf{IDM} = \begin{bmatrix} \ddot{q}_1 & -g\cos(q_1) & g\sin(q_1) & \dot{q}_1 & \mathrm{sign}(\dot{q}_1) \end{bmatrix} \\ \boldsymbol{\chi} = \begin{bmatrix} ZZ_{1R} & MX_1 & MY_1 & Fv_1 & Fc_1 \end{bmatrix}^T \end{cases}$$

Only 1 joint studied :

revolute joint

→ 1 *dof*

Modeling rigid model with quasi-irreversible gearbox

New inverse dynamic model :

$$\tau_{m1} = Ia_1\ddot{q}_1 + \ldots$$

$$0.5\left[\left(1+\mathrm{sign}\left(\tau_{L1}\dot{q}_1\right)\right)r1+\left(1-\mathrm{sign}\left(\tau_{L1}\dot{q}_1\right)\right)r2\right]\left[ZZ_1\ddot{q}_1 - MX_1 g\cos(q_1)+MY_1 g\sin(q_1)\right]+\ldots$$

$$0.5\left(1+\mathrm{sign}\left(\dot{q}_1\right)\right)\left(Fcp_1+Fvp_1\dot{q}_1\right)+0.5\left(1-\mathrm{sign}\left(\dot{q}_1\right)\right)\left(Fcn_1+Fvn_1\dot{q}_1\right)$$

New inverse dynamic model linear to parameters:

$$\boldsymbol{\tau} = \tau_{m1}$$

$$\mathbf{IDM} = \begin{bmatrix}\ddot{q}_1 & s_1\ddot{q}_1 & -s_1 g\cos(q_1) & s_1 g\sin(q_1) & s_2\ddot{q}_1 & -s_2 g\cos(q_1) & s_2 g\sin(q_1) & s_3 & s_3\dot{q}_1 & s_4 & s_4\dot{q}_1\end{bmatrix}$$

$$\boldsymbol{\chi} = \begin{bmatrix}Ia_1 & r1ZZ_1 & r1MX_1 & r1MY_1 & r2ZZ_{1R} & r2MX_1 & r2MY_1 & Fcp_1 & Fvp_1 & Fcn_1 & Fvn_1\end{bmatrix}^T$$

with

$$s_1 = 0.5\left(1+\mathrm{sign}\left(\tau_{L1}\dot{q}_1\right)\right)$$

$$s_2 = 0.5\left(1-\mathrm{sign}\left(\tau_{L1}\dot{q}_1\right)\right)$$

$$s_3 = 0.5\left(1+\mathrm{sign}\left(\dot{q}_1\right)\right)$$

$$s_4 = 0.5\left(1-\mathrm{sign}\left(\dot{q}_1\right)\right)$$

Approximation

$$\text{sign}\left(\tau_{L1}\dot{q}_1\right) = \text{sign}\left(\left(ZZ_1\ddot{q}_1 - MX_1 g\cos(q_1) + MY_1 g\sin(q_1)\right)\dot{q}_1\right)$$
$$\approx \text{sign}\left(\left(ZZ_1^{ap}\ddot{q}_1 - MX_1^{ap} g\cos(q_1) + MY_1^{ap} g\sin(q_1)\right)\dot{q}_1\right)$$

For the Discovery IFS 730 :

$ZZ_1^{ap} > 0$ (physic…)

$MX_1^{ap} = 0$

$MY_1^{ap} = 0$

Balanced system (C-arm)

Data acquisition and filtering

- **Motor position** q_1 measured with motor encoder,
- **Motor current** I_1 measured by the controller,

- Motor torque :

$$\tau_{m1} = \underbrace{g_{\tau 1}}_{\text{Gain of joint drive chain}} I_1$$

- Sample frequency of measurements : **1 kHz**,
- Cut-off frequency of Butterworth filter : **30 Hz**,
- Cut-off frequency of // filter : **5 Hz,**
- Exiting reference trajectories : trapezoidal velocity + position levels

Experimental results

Essential parameters	$\hat{X}$	$\%\sigma_{\hat{X}_r}$
$g_{\tau 1}ZZ_1r1$	3.40	1.6
$g_{\tau 1}ZZ_1r2$	1.35	3.2
$g_{\tau 1}Fcp_1$	1.50	3.0
$g_{\tau 1}Fcn_1$	1.39	3.6

$$\|\mathbf{W}\boldsymbol{\chi}\text{-}\mathbf{Y}\| / \|\mathbf{Y}\| = 9.4\%$$

r1/r2=2.51 → **gear efficiency 2.5x better for $P_{L1}>0$** (compared $P_{L1}<0$)

Balanced system : MX_1 and $MY_1 = 0$

Conclusion

- ***IDIM-LS* method : simple and efficient identification method**

- **Simple example of identification of medical device with quasi-irreversible gear box**

- **Current work : identification of new medical device of General Electric with quasi-irreversible gear box and flexibilities (MammoNExT project – confidential)**