

# 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  $\ddot{\mathbf{q}}$

$$\text{motor torques } \left\{ \begin{array}{l} \tau_{\text{mdi}_m} = \overbrace{\mathbf{I} \mathbf{a} \ddot{\mathbf{q}}}^{\text{rotor inertias}} + \tau_f + \tau_L \quad \text{with} \\ \tau_L = \underbrace{\mathbf{M}(\mathbf{q}) \ddot{\mathbf{q}}}_{\text{bodies inertia matrix}} + \overbrace{\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}}) \dot{\mathbf{q}}}^{\text{centrifugal and Coriolis torques}} + \underbrace{\mathbf{Q}(\mathbf{q})}_{\text{gravity torques}} \end{array} \right.$$

$$\text{friction torques } \left\{ \tau_f = \mathbf{F} \mathbf{v} \dot{\mathbf{q}} + \mathbf{F} \mathbf{c} \text{sign}(\dot{\mathbf{q}}) \right.$$

All parameters and variables expressed in units on joint side.

# Torques linear to parameters

➤ With ***DHM*** notation :

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

$$\tau_{\text{mdi}_m} = \mathbf{I}a\ddot{\mathbf{q}} + \tau_f + \tau_{\text{mdi}_L}$$



$$\tau_{\text{mdi}_m} = \mathbf{MDI}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}})\chi$$

➤ dynamic parameters  $\chi$ :

- inertial parameters ( $Ia$ ,  $XX$ ,  $XZ$ , ...,  $ZZ$ )
- gravity parameters ( $M$ ,  $MX$ ,  $MY$ ,  $MZ$ )
- viscous and Coulomb frictions ( $F_v$  et  $F_c$ )

# Inverse Dynamic Identification Model with Least-Squares

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



- sampling
- // filtering and downsampling of  $\mathbf{Y}$  and  $\mathbf{W}$

➤ overdetermined system:  $\mathbf{Y} = \mathbf{W}(\hat{\mathbf{q}}, \hat{\dot{\mathbf{q}}}, \hat{\ddot{\mathbf{q}}})\boldsymbol{\chi} + \boldsymbol{\rho}$

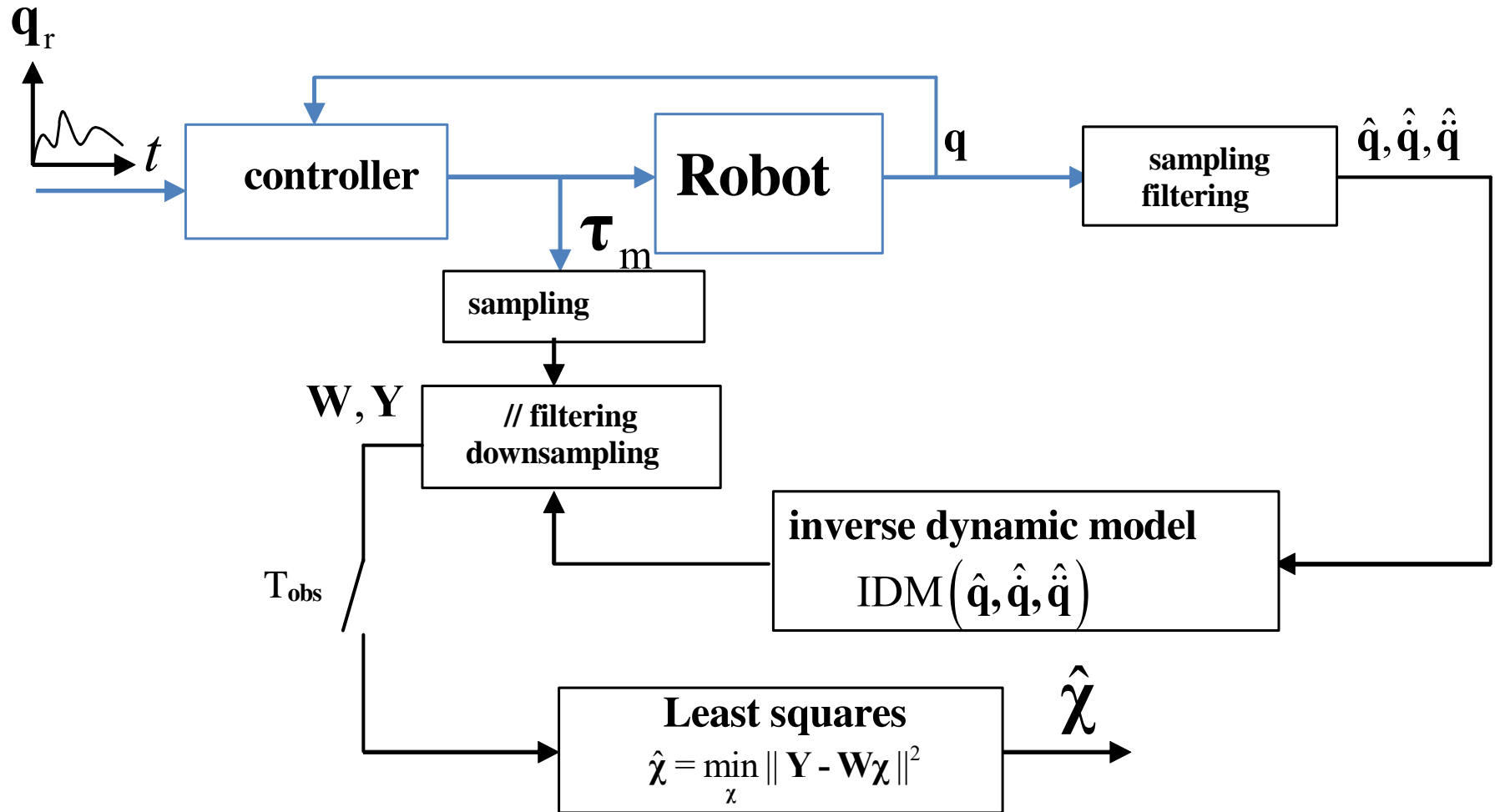
# Dynamic parameters estimation

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

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

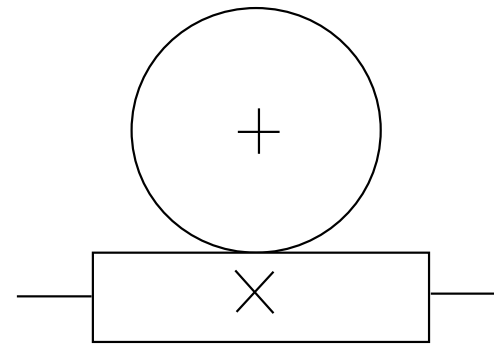
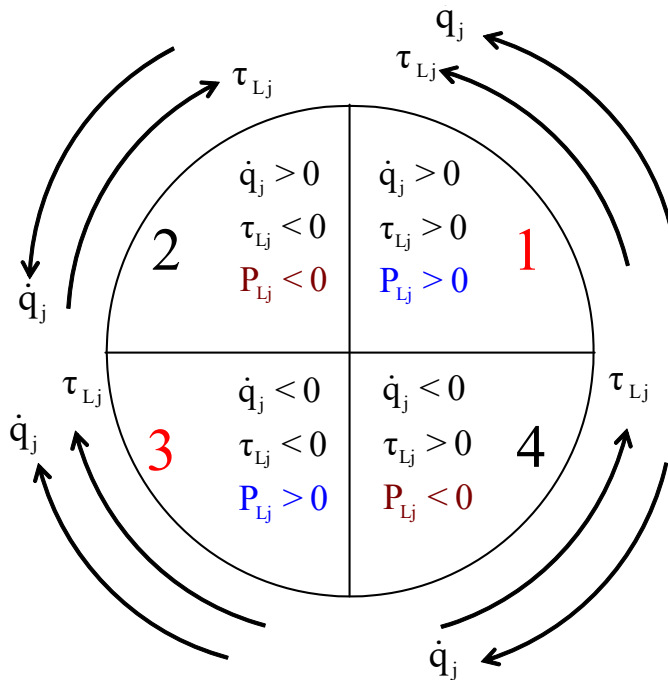


# IDIM-LS method



# Issue of medical devices

## ➤ Use of quasi-irreversible gearbox



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

$$\neq$$

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

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

# Inverse Dynamic Model

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

$$\boldsymbol{\tau}_{\text{mdi}_m} = \mathbf{I}\mathbf{a}\ddot{\mathbf{q}} + \boldsymbol{\tau}_{\text{fp}} + \boldsymbol{\tau}_{\text{fn}} + \mathbf{R}\boldsymbol{\tau}_{\text{mdi}_L}$$

$$\tau_{\text{fpj}} = 0.5 \left( 1 + \text{sign}(\dot{q}_j) \right) \left( F_{\text{cp}_j} + F_{\text{vp}_j} \dot{q}_j \right)$$

$$\tau_{\text{fnj}} = 0.5 \left( 1 - \text{sign}(\dot{q}_j) \right) \left( F_{\text{cn}_j} + F_{\text{vn}_j} \dot{q}_j \right)$$

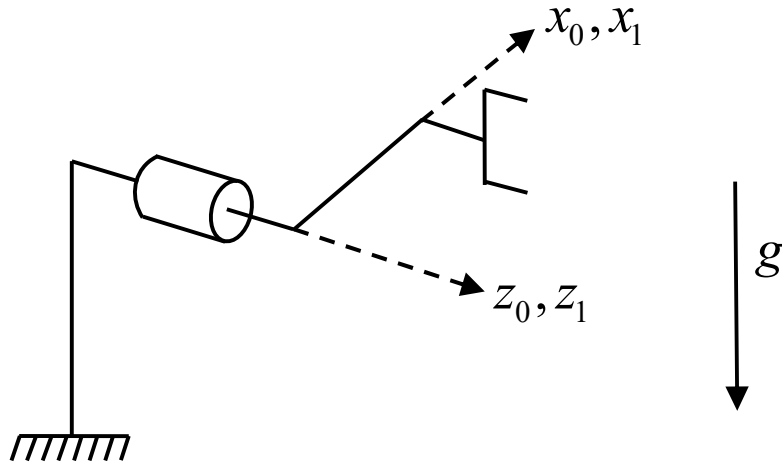
$$\mathbf{R}_{jj} = 0.5 \left[ \left( 1 + \text{sign}(\tau_{Lj} \dot{q}_j) \right) r_{1j} + \left( 1 - \text{sign}(\tau_{Lj} \dot{q}_j) \right) r_{2j} \right]$$

# 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



**Only 1 joint studied :**  
 revolute joint  
 $\rightarrow$  1 *dof*

Classic inverse dynamic model :

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

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

Inverse dynamic model linear to parameters:

$$\tau_m = \mathbf{IDM}(\mathbf{q}, \dot{\mathbf{q}}, \ddot{\mathbf{q}}) \boldsymbol{\chi} + \mathbf{e}$$

with

$$\begin{cases} \tau_m = \tau_{m1} \\ \mathbf{IDM} = [\ddot{q}_1 \quad -g \cos(q_1) \quad g \sin(q_1) \quad \dot{q}_1 \quad \text{sign}(\dot{q}_1)] \\ \boldsymbol{\chi} = [ZZ_{1R} \quad MX_1 \quad MY_1 \quad Fv_1 \quad Fc_1]^T \end{cases}$$

# Modeling rigid model with quasi-irreversible gearbox

New inverse dynamic model :

$$\tau_{ml} = I a_1 \ddot{q}_1 + \dots$$

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

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

New inverse dynamic model linear to parameters:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{ml}$$

$$\mathbf{IDM} = [\ddot{q}_1 \quad s_1 \ddot{q}_1 \quad -s_1 g \cos(q_1) \quad s_1 g \sin(q_1) \quad s_2 \ddot{q}_1 \quad -s_2 g \cos(q_1) \quad s_2 g \sin(q_1) \quad s_3 \quad s_3 \dot{q}_1 \quad s_4 \quad s_4 \dot{q}_1]$$

$$\boldsymbol{\chi} = [I a_1 \quad r1 ZZ_1 \quad r1 MX_1 \quad r1 MY_1 \quad r2 ZZ_{1R} \quad r2 MX_1 \quad r2 MY_1 \quad Fcp_1 \quad Fvp_1 \quad Fcn_1 \quad Fvn_1]^T$$

with

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

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

$$s_3 = 0.5 (1 + \text{sign}(\dot{q}_1))$$

$$s_4 = 0.5 (1 - \text{sign}(\dot{q}_1))$$

# Approximation

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

For the Discovery IFS 730 :

$$ZZ_1^{\text{ap}} > 0 \quad (\text{physic...})$$

$$MX_1^{\text{ap}} = 0$$

$$MY_1^{\text{ap}} = 0$$

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	$\hat{\chi}$	$\% \sigma_{\hat{\chi}_r}$
$g_{\tau_1} Z Z_1 r_1$	3.40	1.6
$g_{\tau_1} Z Z_1 r_2$	1.35	3.2
$g_{\tau_1} F_{cp_1}$	1.50	3.0
$g_{\tau_1} F_{cn_1}$	1.39	3.6

$$\|W\chi - Y\| / \|Y\| = 9.4\%$$

$r_1/r_2 = 2.51 \rightarrow$  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)**