Modélisation et identification d'un bras manipulateur sous-marin actionné de manière hétérogène

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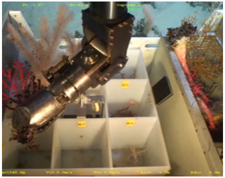
Outline

HROV *Ariane*'s missions

Some missions and challenges:

Seabed core sampling

- control vertical and horizontal forces
- keep the coring tool vertical



Storage of a sample

- avoid collisions
- don't mix different samples together

Collect of a gorgonian

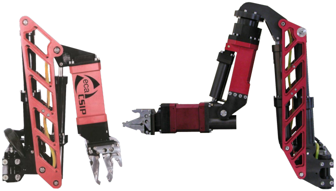
- avoid collisions
- control of the grip strength

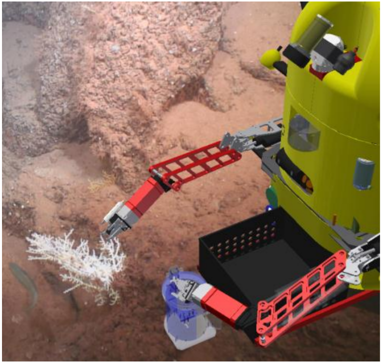
The manipulator arms of *Ariane*

Control modes :
human given speed reference, in cartesian or joint space

State of the manipulator arms :
given by position sensors (count of the steps of the motor)

Speed of the joints :
up to 15 deg/s





Tasks example

Objectives of the project

Objectives

- automation of recurrent tasks
  - seabed coring
  - storage of samples in the basket
- dual-arm manipulation of cumbersome samples

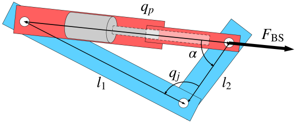
Steps

1. dynamic modeling of the manipulator arms, including the actuators dynamics
2. identification of the dynamic parameters of the models
3. determination of dual-arm manipulation strategies adapted to underwater manipulation

Focus of this presentation

The dynamic modeling of the arms of *Ariane* with an emphasis placed upon their actuators, and the identification of the parameters of their models.

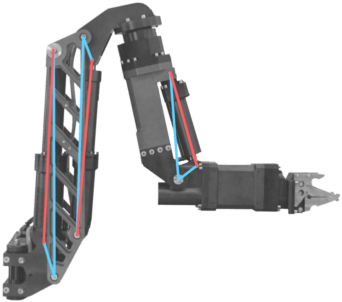
Description of the actuators of *Ariane*'s manipulator arms



Drawing of a revolute joint actuated by a linear actuator

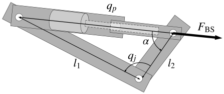
Motivations

- non-linear transformation of the rotation of the motor into the rotation of the joint
- the inertia and mass of the actuators cannot be neglected

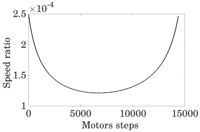


The revolute joints actuated by linear actuators of the 6-DOF manipulator arm.

Kinematic modeling of a revolute joint actuated by a linear actuator



Drawing of a revolute joint actuated by a linear actuator



Ratio $\dot{q}/\dot{q}_m$ against the motor's coordinate

- Linear actuator's length

$$q_p = \frac{q_{p_{\max}} - q_{p_{\min}}}{q_{m_{\max}} - q_{m_{\min}}} q_m + q_{p_{\min}} \tag{1}$$

- Inner joint's coordinate

$$q_j = \arccos\left(\frac{l_1^2 + l_2^2 - q_p^2}{2 l_1 l_2}\right) \tag{2}$$

- Modified Denavit-Hartenberg joint's coordinate

$$q = \operatorname{rev} q_j + \text{offset} \tag{3}$$

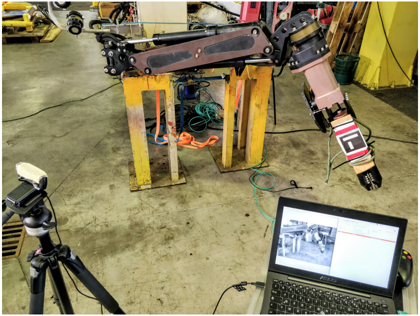
- Parameters of the model

l_1, l_2	lengths measured on the actuator
$q_{p_{\max}}$, $q_{p_{\min}}$	lengths measured on the actuator
$q_{m_{\max}}$, $q_{m_{\min}}$	values read by the motor drives at each joint limit
rev	-1 or 1
offset	measured by placing the joint in particular positions

Optimization of the actuators parameters 1/2

Acquisition of a ground truth for optimizing the actuators parameters:

1. a fiducial marker is fixed to the arm, in the field of view of a calibrated camera
2. the pose of the marker is estimated using ArUco[1]
3. the motor coordinates and the poses of the marker are recorded while one joint of the arm moves from one limit to the other one



The setup used to acquire the data required for the optimization of the actuators' parameters

We define and solve the following optimization problem:

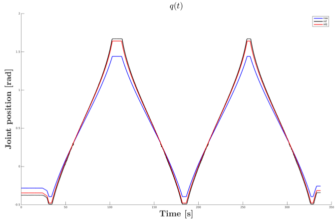
$$\underset{X}{\text{minimize}} \quad \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\dot{\hat{q}}_X(i) - \dot{q}(i)\right)^2} \quad , \quad X = \left[l_1, l_2, q_{p_{\min}}, q_{p_{\max}}\right]^\top$$

[1] S. Garrido-Jurado and R. Muñoz-Salinas and F.J. Madrid-Cuevas and M.J. Marín-Jiménez, Automatic generation and detection of highly reliable fiducial markers under occlusion

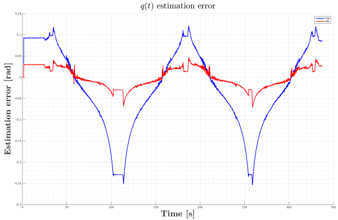
Optimization of the actuators parameters 2/2

This allows to refine the value of l_1, l_2, $q_{p_{\min}}$, and $q_{p_{\max}}$; and thus to improve to estimation of the joint coordinates only based on the count of the motors steps:

Raw RMSE	Optimized RMSE	Improvement
0.0983 rad	0.0235 rad	76.1 %



Joint coordinate estimation based on measured (blue) and optimized (red) model parameters



Error of the joint coordinate estimation based on measured (blue) and optimized (red) model parameters

Dynamic modeling of a revolute joint actuated by a linear actuator

Equation of the gear motor:

$$\tau_m = k_T\, i - r^2\, \left(J_m\, \ddot{q}_m + f_{v_m}\, \dot{q}_m + f_{s_m}\, \mathrm{sign}(\dot{q}_m)\right) \tag{4}$$

Equation of the ball-screw:

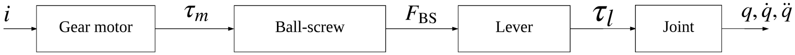
$$F_{\mathrm{BS}} = \frac{2\pi}{p}\, \tau_m - I_{\mathrm{BS}}\, \ddot{q}_p - f_{v_{\mathrm{BS}}}\, \dot{q}_p - f_{s_{\mathrm{BS}}}\, \mathrm{sign}(\dot{q}_p) \tag{5}$$

Equation of the lever:

$$\tau_l = l_2\, \sin(\alpha)\, F_{\mathrm{BS}} \tag{6}$$

Which gives the equation of the whole actuator:

$$\tau_l = k_L(q)\, i - m_{L,eq}(q, \ddot{q}) - f_{L,eq}(q, \dot{q}) \tag{7}$$



Dynamic modeling of the whole manipulator arm

Equation of a directly actuated revolute joint:

$$\tau_D = k_T\, i - r^2\, \left(J_m\, \ddot{q}_m + f_{v_m}\, \dot{q}_m + f_{s_m}\, \mathrm{sign}(\dot{q}_m)\right) \tag{8}$$

Equation of a revolute joint actuated by a linear actuator (levered):

$$\tau_L = k_L(q)\, i - m_{L,eq}(q, \ddot{q}) - f_{L,eq}(q, \dot{q}) \tag{9}$$

It results in the following multidimensional model of all the actuators of an arm:

$$\boldsymbol{\tau} = \boldsymbol{K}(\boldsymbol{q})\, \boldsymbol{i} - \boldsymbol{M}_{\text{actuators}}(\boldsymbol{q})\, \ddot{\boldsymbol{q}} - \boldsymbol{N}_{\text{actuators}}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \tag{10}$$

where

$$\boldsymbol{K}_{j,j}(\boldsymbol{q}) = \begin{cases} k_{T,j} & \text{if joint } j \text{ is direct} \\ k_{L,j}(q) & \text{if joint } j \text{ is levered} \end{cases} \tag{11}$$

Dynamic models of the full manipulator arms

The classical model of a manipulator arm is:

$$\boldsymbol{\tau} = \boldsymbol{M}(\boldsymbol{q})\,\ddot{\boldsymbol{q}} + \boldsymbol{N}(\boldsymbol{q},\dot{\boldsymbol{q}}) \tag{12}$$

and the expression of the torque is given by:

$$\boldsymbol{\tau} = \boldsymbol{K}(\boldsymbol{q})\,\boldsymbol{i} - \boldsymbol{M}_{\text{actuators}}(\boldsymbol{q})\,\ddot{\boldsymbol{q}} - \boldsymbol{N}_{\text{actuators}}(\boldsymbol{q},\dot{\boldsymbol{q}}) \tag{13}$$

So by mixing (12) and (13), we obtain:

$$\boldsymbol{K}(\boldsymbol{q})\,\boldsymbol{i} = \boldsymbol{M}^{\star}(\boldsymbol{q})\,\ddot{\boldsymbol{q}} + \boldsymbol{N}^{\star}(\boldsymbol{q},\dot{\boldsymbol{q}}) \tag{14}$$

with the following definitions:

$$\begin{aligned} \boldsymbol{M}^{\star}(\boldsymbol{q}) &= \boldsymbol{M}(\boldsymbol{q}) + \boldsymbol{M}_{\text{actuators}}(\boldsymbol{q}) \\ \boldsymbol{N}^{\star}(\boldsymbol{q},\dot{\boldsymbol{q}}) &= \boldsymbol{N}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{N}_{\text{actuators}}(\boldsymbol{q},\dot{\boldsymbol{q}}) \end{aligned} \tag{15}$$

Identification of the parameters of the 4-DOF arm of *Ariane*

The dynamic model of the arm is linear in its dynamic parameters, so we define:

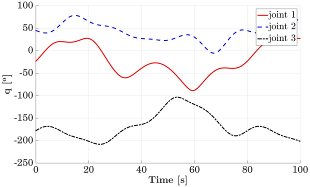
$$\begin{aligned}\boldsymbol{\Phi}^{\star} &= \boldsymbol{K}^{-1}(\boldsymbol{q})\ [\boldsymbol{\Phi}, \boldsymbol{\Phi}_{\text{actuators}}] \\ \boldsymbol{\theta}^{\star} &= \left[\boldsymbol{\theta}^{T}, \boldsymbol{\theta}^{T}_{\text{actuators}}\right]^{T}\end{aligned} \tag{16}$$

to express the dynamic identification model of the system as:

$$\boldsymbol{\Phi}^{\star}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}\right)\ \boldsymbol{\theta}^{\star}\ =\ \boldsymbol{i} \tag{17}$$

We finally estimate the dynamic parameters by solving the overdetermined system created using the objects defined in (19):

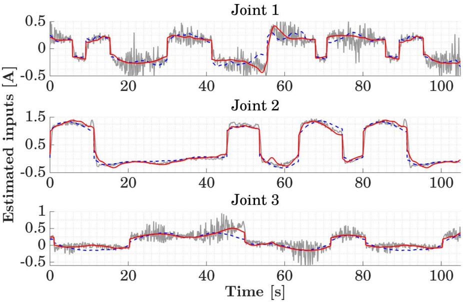
$$\hat{\boldsymbol{\theta}}^{\star} = \boldsymbol{F}^{+}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}\right)\ \boldsymbol{b} \tag{18}$$



A reference excitation trajectory for the identification of the model

$$\begin{aligned}\boldsymbol{F} &= \begin{bmatrix} \boldsymbol{\Phi}^{\star}\left(\boldsymbol{q}\left(0\right), \dot{\boldsymbol{q}}\left(0\right), \ddot{\boldsymbol{q}}\left(0\right)\right) \\ \vdots \\ \boldsymbol{\Phi}^{\star}\left(\boldsymbol{q}\left(N\right), \dot{\boldsymbol{q}}\left(N\right), \ddot{\boldsymbol{q}}\left(N\right)\right) \end{bmatrix} \\ \boldsymbol{b} &= \left[\boldsymbol{i}\left(0\right) \cdots \boldsymbol{i}\left(N\right)\right]^{T}\end{aligned} \tag{19}$$

Experimental validation of the model



The real current (solid gray line) is compared to the estimated input current, without (blue dashed line) and with (red solid line) actuators' dynamics, obtained as:

$$\hat{\boldsymbol{b}} = \boldsymbol{F}\left(\boldsymbol{q}, \dot{\boldsymbol{q}}, \ddot{\boldsymbol{q}}\right)\, \hat{\boldsymbol{\theta}}^{\star} \tag{20}$$

We also compute the root mean square error of the estimation in both cases:

$$\mathrm{RMSE}(\hat{\boldsymbol{b}}) = \sqrt{\mathrm{E}((\hat{\boldsymbol{b}} - \boldsymbol{b})^2)} \tag{21}$$

	Joint 1 [%]	Joint 2 [%]	Joint 3 [%]
without actuators dynamics	0.129	0.154	0.152
with actuators dynamics	0.117	0.128	0.122
improvement (percent)	9.80	16.8	19.9

Overview

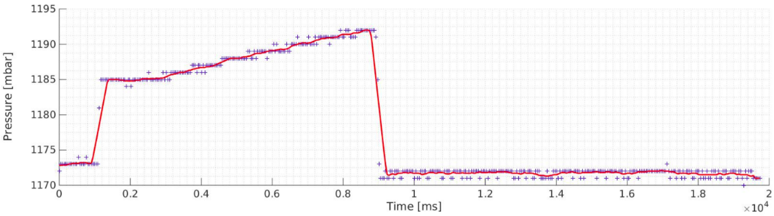
Motivations:

- the derived models are not perfect: calibration issues, unmodeled effects, no groundtruth
- in order to manipulate an object with both arms, we need to introduce compliance in the kinematic chain
- hence the design of compliant grasping tools

(a) (b) (c)

Compliant tool for dual-arm manipulation of breakable samples

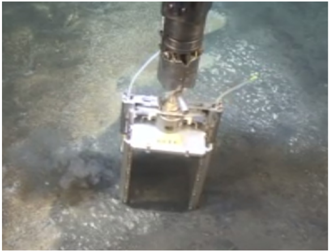
Example: bottle filling



Evolution of the pressure inside the tool measured while filling a bottle of water placed on the tool.

Modeling of the arms

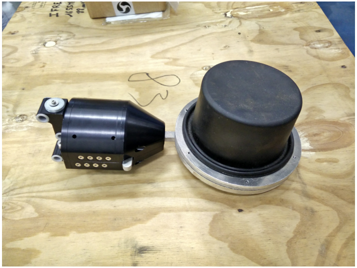
- specific actuators require a specific modeling
- a kinematic and dynamic model of *Ariane*'s manipulator arms has been derived
- these models describe the behaviour of the manipulator arms more accurately
- the estimation of the grippers pose is also more accurate



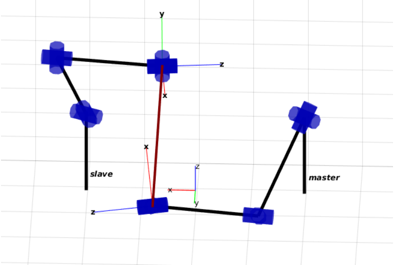

Some tasks that could be automated thanks to an improved knowledge of the behaviour of *Ariane*'s manipulator arms

Grasping tools

- to compensate for unmodeled effects, compliant tools have been designed and prototyped
- this allows to perform dual-arm manipulation of cumbersome and breakable samples
- a control law needs to be designed to control both arms for this task



(a)



(b)

(a) compliant tool held by a gripper - (b) simulation of the dual-arm system

Thank you for you attention

Modified DH parameters of the manipulator arms

Table : Geometric parameters of the 6-DOF manipulator arm

Joint	d [m]	r [m]	α [rad]	l_1 [m]	l_2 [m]
1	0	0	0	0.323	0.0629
2	0.180	0	$\frac{\pi}{2}$	0.099	0.641
3	0.685	0	0	0.616	0.068
4	-0.170	0.488	$-\frac{\pi}{2}$	-	-
5	0	0	$\frac{\pi}{2}$	0.306	0.058
6	0	0.300	$-\frac{\pi}{2}$	-	-

Table : Geometric parameters of the 4-DOF manipulator arm

Joint	d [m]	r [m]	α [rad]	l_1 [m]	l_2 [m]
1	0	0	0	0.323	0.058
2	0.116	0	$\frac{\pi}{2}$	0.073	0.537
3	0.443	0	0	0.489	0.054
4	-0.1	0.436	$-\frac{\pi}{2}$	-	-

Excitation trajectories optimisation

Trajectories parameterisation:

$$q^i(t) = \sum_{k=1}^{N^i} \left[\frac{a_k^i}{\omega_f\, k} \sin\left(\omega_f\, k\, t\right) - \frac{b_k^i}{\omega_f\, k} \cos\left(\omega_f\, k\, t\right) \right] + q_0^i$$

Criteria to minimise:

$$c = \mathrm{cond}(\boldsymbol{F}), \text{ with } \boldsymbol{F} = \Big[\boldsymbol{\Phi}^\star \left(\boldsymbol{q}\,(t)\,, \dot{\boldsymbol{q}}\,(t)\,, \ddot{\boldsymbol{q}}\,(t) \right) \Big]_i$$

Table : Constraints of the optimization problem

	Unit	Joint 1	Joint 2	Joint 3
$\boldsymbol{q}_m$	[inc]	$[0; 20850]$	$[0; 6810]$	$[0; 26750]$
$\dot{\boldsymbol{q}}_{m,\max}$	[inc/s]	2000	600	2000
$\ddot{\boldsymbol{q}}_{m,\max}$	[inc/s^2]	20000	6000	20000
$\boldsymbol{q}$	[$^\circ$]	$[-90; 32]$	$[7; 94]$	$[110; 244]$
$\dot{\boldsymbol{q}}_{\max}$	[$^\circ$/s]	28	9	25