RobEcolo: Design of a Wooden Industrial Robot

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Séminaire recherche de l'axe M3G – Institut Pascal

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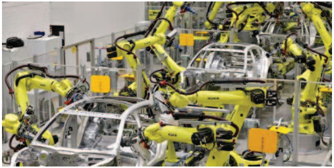
Introduction

Eco-design in Robotics

Interest?



stock : 1 500 000

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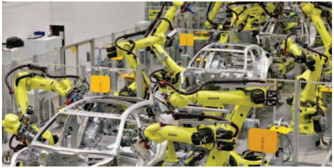

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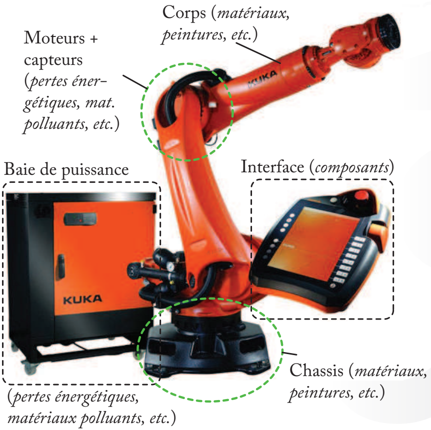
But

- Sales of robots increase by 20 % per year
- Political context: lowering by 40 % the GG emitted and by 27 % our electrical cons. for 2030 in EU
- Lowering the electrical invoice / "Green washing"
- **Why impacting the environment if we can do differently?**

Introduction

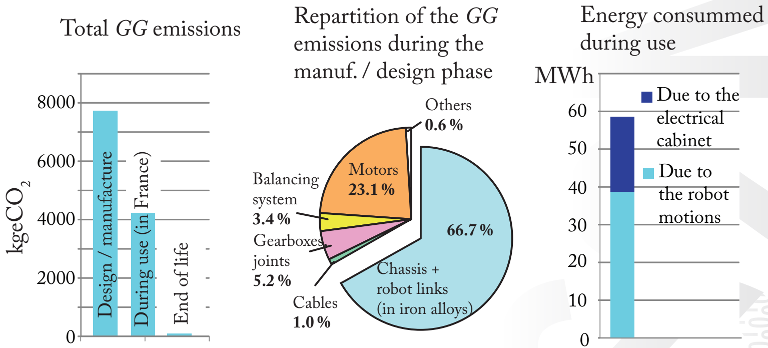
Factors of environmental impact for an industrial robot (**process disreg.**)



Introduction

A few data

Study made on a Kuka KR270 achieved by Fizians Env. – *Do not take into account the achievement of the electrical cabinet*



The CO_2 release during use in other coutries is much bigger as most of the energy production in France is due to nuclear power plants (releasing much less CO_2 than other types of plants)

Introduction

Eco-design in Robotics

Two main directions for improvements (**excepting process**)

- Decrease of the electrical consumption (99 % of the actual research works)
  Eco-design?! (not necessarily guided by this concept)
  - Re design (robot, electrical cabinet, robot cell, etc.)
  - Motion planning
  - New types of actuators
  - Series of robots Eco-Bot
- Decrease of the use of impacting materials
  - Lightweight robots
  - Design by using materials with low environmental impacts

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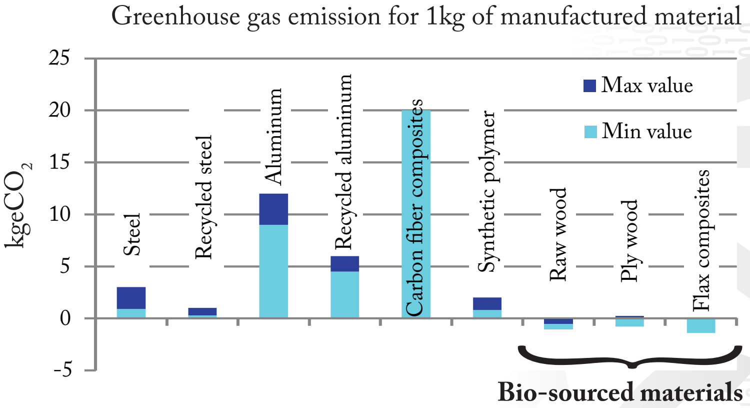
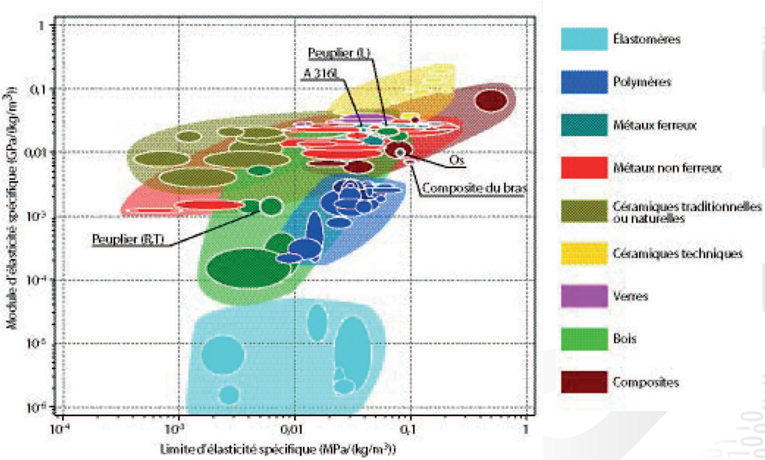
    ⇒ Project RobEcolo

Environmental impact of several materials



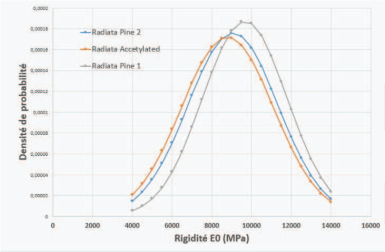
Ratio stiffness / mass of several materials

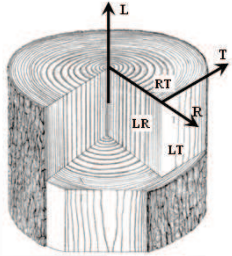


Choice of the material

Bio-sourced materials

+ low environmental impact
+ good ratio stiffness-to-mass
+ widely used in the past (XIXth century, planes up to WW2, ...)
– dispersion of mechanical properties
– non-isotropic materials
– variability of the dimension with the change of humidity
– durability of certain composites
– aspect “old-fashioned”

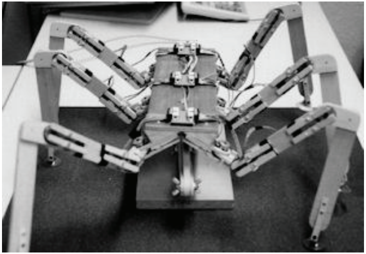


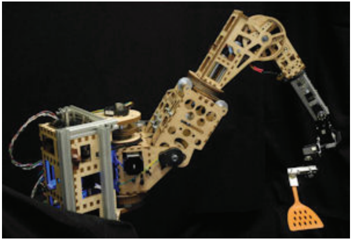


Already some robots made of wood

Few of them are eco-designed

Eco-design or "Not eco-design" ?





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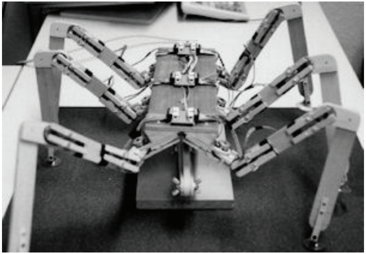

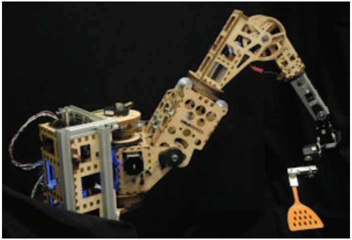

Not eco-design!

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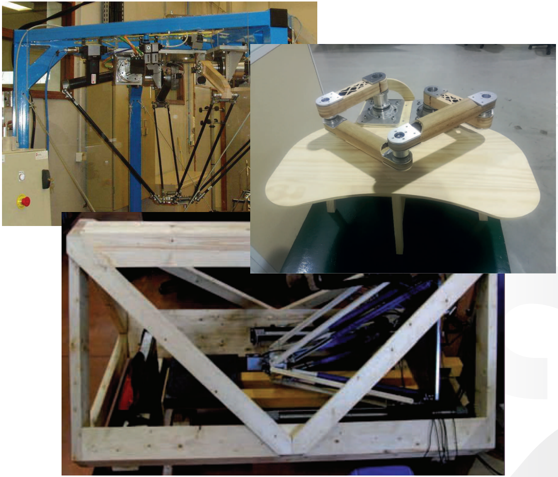

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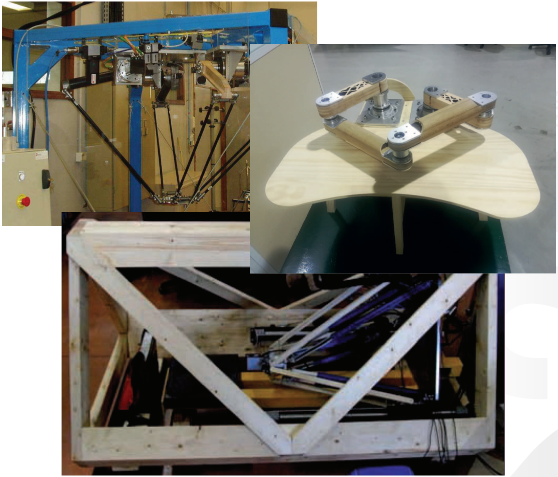

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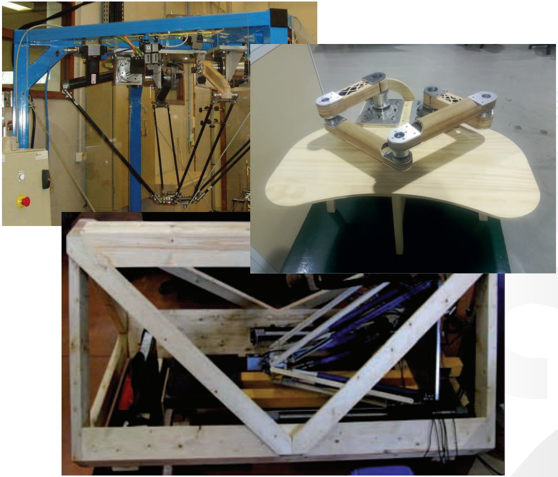
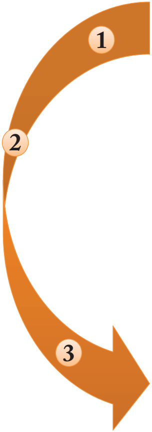


Are we able to achieve an accurate and stiff robot made of bio-sourced materials? (*five-bar mechanism*)

Methodology adopted in RobEcolo



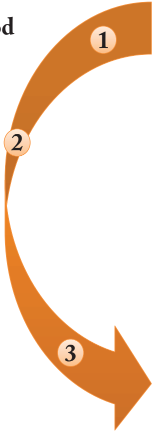
RobEcolo

LS2N + ESB

243 k€

Methodology adopted in RobEcolo

Choice of wood



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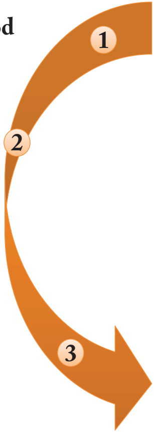
Robust design approaches

↓

Predictive Elastostatic and Elastodynamic Model



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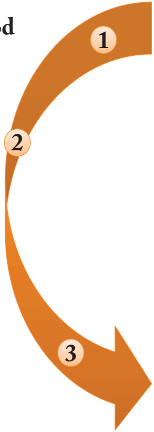
Predictive Elastostatic and Elastodynamic Model

Sensor-based control



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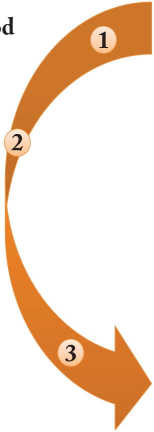

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Choice of the material

Which type of wood?

- Raw wood
- Treated raw wood
- Ply wood

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Choice of Accoya

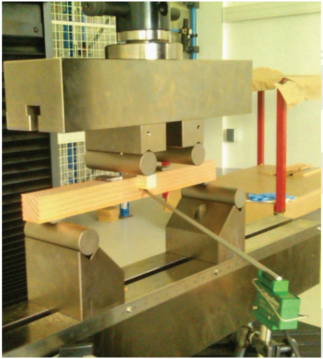
- Acetylated wood: treatment but no pb of end-of-life
- Good dimensional stability
- Two different species: beech (hardwood) and pine (softwood)
- Mechanical properties not well-known

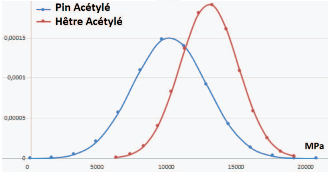
Bridge, Accoya, ply wood
Sneek, The Netherlands

Accoya properties

Characterization of

- Stiffness properties (3 Young's moduli, 6 Poisson ratios!!)

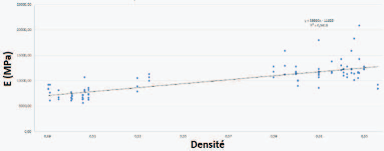


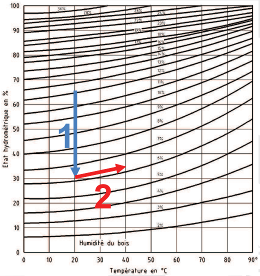


Accoya properties

Characterization of

- Stiffness properties (3 Young's moduli, 6 Poisson ratios!!)
- Density properties
- Dilatation (humidity + temperature)



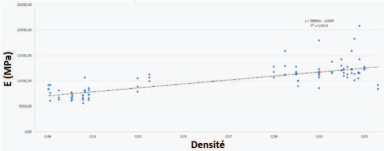


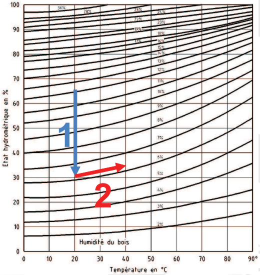
Accoya properties

Characterization of

- Stiffness properties (3 Young's moduli, 6 Poisson ratios!!)
- Density properties
- Dilatation (humidity + temperature)

⇒ Accoya is a good choice for our purpose





Choice of the model

Compromise between

- Accuracy
- Simplicity

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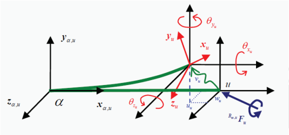
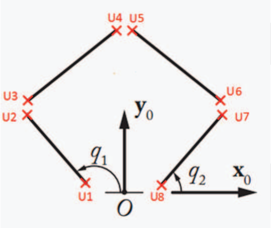
⇒ Bernoulli model for beams and MSA





$$
{}^{R_0}\mathbf{K}_{tot} = \begin{bmatrix}
{}^{R_0}\boldsymbol{K}^1_{22} & 0_6 & 0_6 & 0_6 & 0_6 & 0_6 \\
0_6 & {}^{R_0}\boldsymbol{K}^2_{11} & {}^{R_0}\boldsymbol{K}^2_{12} & 0_6 & 0_6 & 0_6 \\
0_6 & {}^{R_0}\boldsymbol{K}^2_{21} & {}^{R_0}\boldsymbol{K}^2_{22} & 0_6 & 0_6 & 0_6 \\
0_6 & 0_6 & 0_6 & {}^{R_0}\boldsymbol{K}^3_{11} & {}^{R_0}\boldsymbol{K}^3_{12} & 0_6 \\
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0_6 & 0_6 & 0_6 & 0_6 & 0_6 & {}^{R_0}\boldsymbol{K}^4_{11}
\end{bmatrix}
$$

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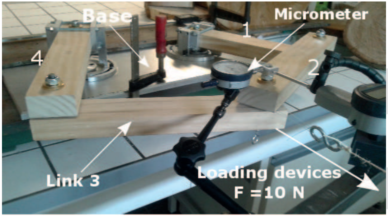
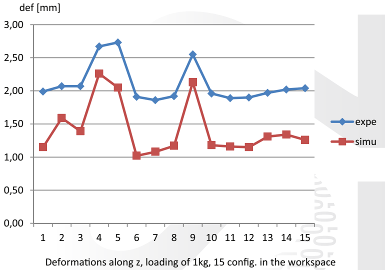


First mockups in order to validate the models

⇒ Problem *(both for deformations and frequencies)*

Why??



Choice of the model

After a time-consuming investigation

⇒ Considerable loss of stiffness due to the holes in wood for joint insertion

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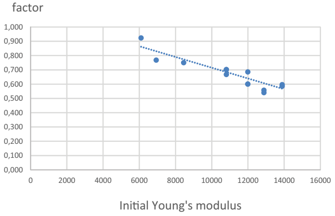
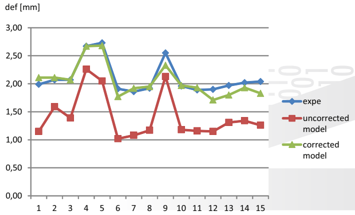
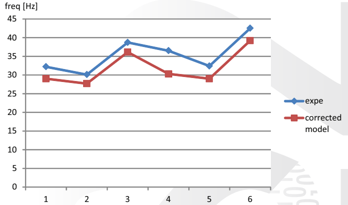
Correction of the material parameters

- Weighting of the material moduli
- Definition of a law of evolution





Deformations along z, loading of 1kg, 15 config. in the workspace



First natual frequency, 6 config. in the workspace

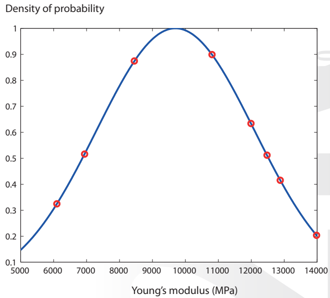
Error < 10 %

Work is still under progress (almost finished)

The results shown here are a brief summary of what we did

Wood properties are dispersed

- Selection of 8 links with 8 different Young's moduli all along the dispersion
- Experiments (deformations and natural frequencies)
  - for a 2R serial robot (4 robot configs.)
  - for a five-bar parallel robot (5 robot configs.)
- Comparison with a model of the dispersion of the deformations and natural frequencies for the robot



Preliminary results shown in L. Kaci, C. Boudaud, S. Briot, P. Martinet, "Elastostatic Modelling of a Wooden Parallel Robot," Proceedings of the 7th IFToMM International Workshop on Computational Kinematics (CK2017), May 22-24, 2017 Futuroscope-Poitiers, France.

Design specifications

Data

- Positioning accuracy of 500 μm
- Deformations lower than of 500 μm under a load of 10 N along z, 100 N along x and y
- For a five-bar mechanism (planar robot with 2 dof)
- With a workspace of 800 mm $\times$ 200 mm
- Performance must be guaranteed in this workspace

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Strategy

- For dealing with variation of the wood parameters (how to ensure a threshold for max. deformations) $\Rightarrow$ **Robust design**

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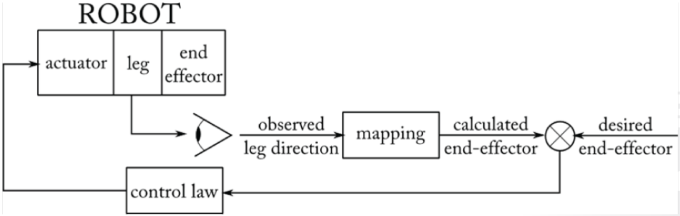
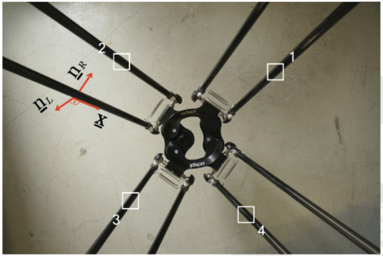
Strategy

- For dealing with variation of the wood parameters (how to ensure a threshold for max. deformations) $\Rightarrow$ **Robust design**
- For dealing with variation of the wood dimension (how to ensure a threshold for max. accuracy) $\Rightarrow$ **Sensor-based control** (*visual servoing*)

Issues with visual servoing





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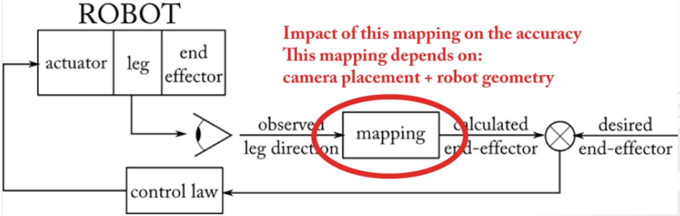
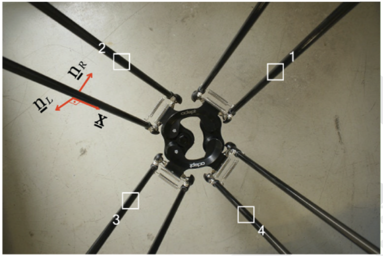




Optimal design process

Design of an Industrial Wooden Robot

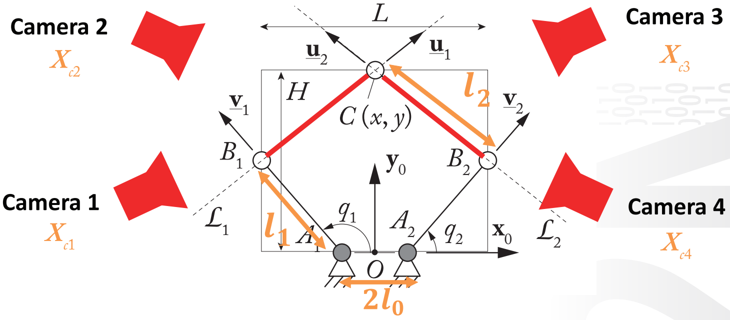
Control-based Design → **Reliable Topology Optimisation**

↓ **Dimensions of the Robot Links**

↓ **Shape of the Robot Links**

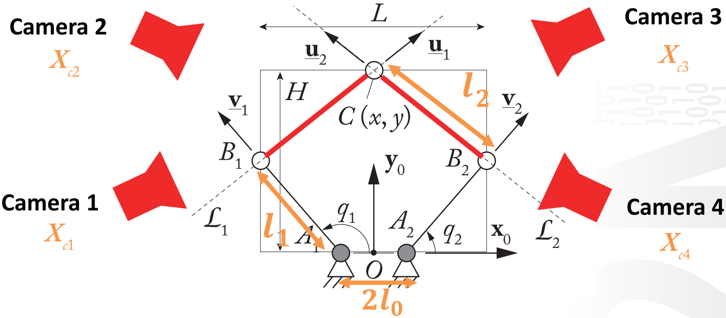
Reach the desired accuracy and stiffness performances

Control-based design



$$
\begin{aligned}
\text{minimize} \quad & A = L\,H \\
\text{over} \quad & \mathbf{X} = [l_0 \;\; l_1 \;\; l_2 \;\; \mathbf{X}_{c1} \;\; \mathbf{X}_{c2} \;\; \mathbf{X}_{c3} \;\; \mathbf{X}_{c4}] \\
\text{subject to} \quad & \ell_{W_L} \geq \ell_{W_0} \\
& h_{W_L} \geq h_{W_0}
\end{aligned}
$$

Control-based design



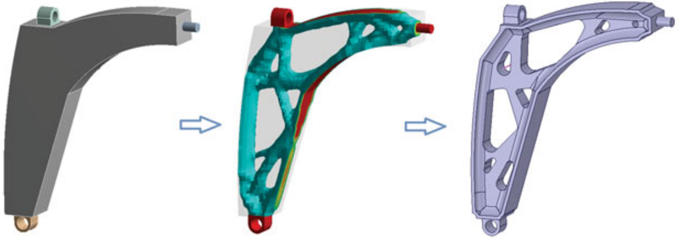
Results

Links	Lengths
l_0 [m]	0.125
l_1 [m]	0.280
l_2 [m]	0.400

Pos/Ori	Camera 3	Camera 4
x_c [m]	0.010	0.020
y_c [m]	0.500	0.100
z_c [m]	0.750	0.100
$rot_2(x)$ [rad]	π	π

Reliable topology optimization

Link shape optimization

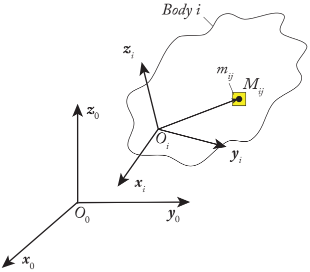


Reliable topology optimization

Problem statement

$$\min f(x) \quad \text{subject to} \quad x \in [-1,1]^n, g(x) \leq 0, h(x) = 0 \qquad (1)$$

- Decision variables: x_i density of i^{th} elements (in fact $\rho_{ij} \equiv j^{th}$ element of the i^{th} body)
- f, g and h: performance indices or structure constraints



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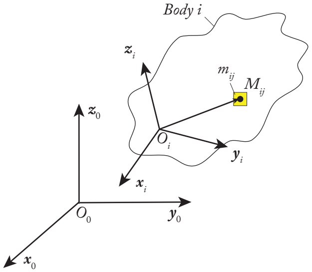


Problem specificities

- Highly nonlinear
- Large number of variables
- Evaluation of function and gradients expensive

Performance criteria

Example of technology-oriented performance criteria

- grouped inertia terms (robot mass, grouped inertia of links) $\Rightarrow$ linear functions
- actuator maximal / RMS torques, energy consumption $\Rightarrow$ linear functions, but depend on the trajectory
- robot static deformations $\Rightarrow$ depend on the trajectory
- natural frequencies $\Rightarrow$ direct link with the controller performance (cutoff frequency), and with the mechanical performance. Depend on the trajectory

Amplitude of vibrations is disregarded because it can be managed through advanced controllers

Performance criteria

Elastic performance

High computational cost

⇒ We propose to use model reduction techniques applied to robot links in order to decrease the computational cost

Problem formulation

Modeling of the linkage elastic behavior

Modified Finite Element model:

- Meshing
- The presence or absence of an element ij parameterized with a material density variable $\rho_{ij} \in [0\,1]$
- Solid Isotropic Material with Penalization (SIMP, [Bendsoe and Sigmund 1999])

$$E_{ij} = E_{\min} + \rho_{ij}^{p}(E_0 - E_{\min}), \text{ with } \rho_{ij} \in [0, 1] \tag{2}$$

- Elementary stiffness matrix

$$\mathbf{K}_{ij} = E_{ij}\mathbf{K}_{ij}^{(0)} = \left(E_{\min} + \rho_{ij}^{p}(E_0 - E_{\min})\right)\mathbf{K}_{ij}^{(0)} \tag{3}$$

Problem formulation

Modeling of the linkage elastic behavior

- Elementary mass matrix

$$\mathbf{M}_{ij} = \rho_{ij}\mathbf{M}^0_{ij} \quad (4)$$

- Use standard techniques for assembling mass and stiffness matrices:
  - for each link
  - for the linkage
- Compute the performance (deformations and natural frequencies)
- TO algorithms needs the performance AND their derivatives wrt the decision variables!
- Speed up the computation by using model reduction techniques [Craig and Bampton, 1968]

Problem formulation

Recall: Bienaymé-Tchebichev theorem

$$\mathbb{P}\left[\left|\|\mathbf{u}_e\| - E(\|\mathbf{u}_e\|)\right| \geq k\sigma(\|\mathbf{u}_e\|)\right] \leq \frac{1}{k^2} \quad (5)$$

where

- $E(.)$: expectation operator
- $\sigma(.)$: standard deviation operator
- k: a positive real
- $\mathbf{u}_e$: deformation vector at given nodes, for a fixed nodal loading $\mathbf{f}$

Criterion used for dealing with reliability of performance

$$E(\|\mathbf{u}_e\|) + k\sigma(\|\mathbf{u}_e\|) \leq u_{max} \quad (6)$$

Problem formulation

Skipping the details

Approximate formulas for $E(\|\mathbf{u}_e\|)$ and $\sigma(\|\mathbf{u}_e\|)$ (and their derivatives) are provided in

Alireza Asadpoure, Mazdak Tootkaboni, James K. Guest, "Robust topology optimization of structures with uncertainties in stiffness – Application to truss structures," Computers and Structures 89 (2011) 1131–1141.

⇒ Valuable when the variation of the parameters is lower than 15 %

Optimal design of a five-bar mechanism

Optimization problem

- objective: to minimize the actuator torques RMS for any trajectory
- constraints:
  - to ensure that $\delta_C < \delta_{\max} = 0.5$ mm under $\mathbf{f}_1 = [0\ N \quad 100\ N \quad 1\ Nm]^T$ and $\mathbf{f}_2 = [100\ N \quad 0\ N \quad -1\ Nm]^T$
  - $\delta_C = E(\|\mathbf{u}_e\|) + k\sigma(\|\mathbf{u}_e\|)$

wherever in the dextrous workspace (discretized with 231 points).

$$
\begin{array}{ll}
\min\limits_{\boldsymbol{\rho}} & F = \overline{\tau}_1^2(\mathcal{T}^*) \\
\text{under} & g_1 = (\delta_C^2(\mathbf{f}_1, \mathbf{q}^*) - \delta_{\max}^2)/\delta_{\max}^2 \leq 0 \\
& g_2 = (\theta_C^2(\mathbf{f}_1, \mathbf{q}^*) - \theta_{\max}^2)/\theta_{\max}^2 \leq 0 \\
& g_3 = (\delta_C^2(\mathbf{f}_2, \mathbf{q}^*) - \delta_{\max}^2)/\delta_{\max}^2 \leq 0 \\
& g_4 = (\theta_C^2(\mathbf{f}_2, \mathbf{q}^*) - \theta_{\max}^2)/\theta_{\max}^2 \leq 0
\end{array}
\tag{7}
$$

Optimal design of a five-bar mechanism

Optimization problem

We developed a method for the selection of the optimal test trajectories and configurations in:
S. Briot and A. Goldsztejn, "Topology Optimization of Industrial Robots: Application to a Five-bar Mechanism," Mechanism and Machine Theory, 2018, Vol. 120, pp. 30-56.

Initial link design

Finite elements

- steel: $E_0 = 12.772$ GPa, $\nu = 0.3$, $cv = 0.15$
- 24132 elements for the proximal links, 22608 elements for the distal links of dimension 1×1 mm (planar elements)
- thickness of 5 cm

(a) Design of the proximal links: initial design domain

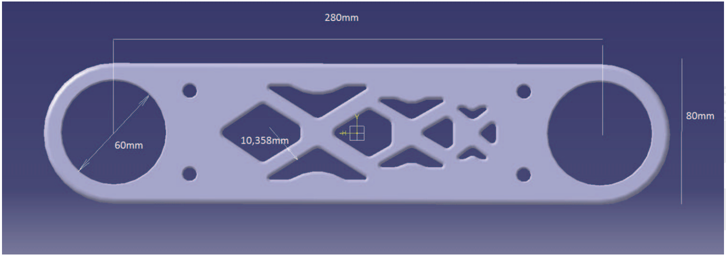
(b) Design of the distal links: initial design domain

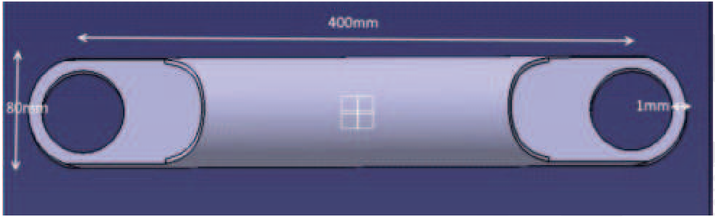
(c) Design of the proximal links: final design

(d) Design of the distal links: final design

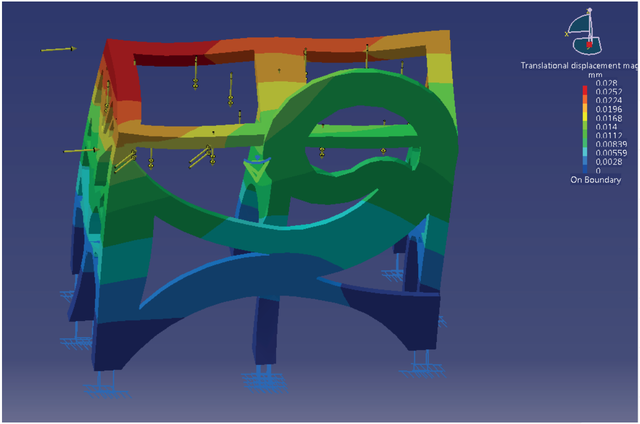
Figure: Evolution of the design of the five-bar links: the links are shown in gray-scale (black elements correspond to $\rho_i = 1$, white elements to $\rho_i = 0$, and gray elements to $0 < \rho_i < 1$)

CAD





CAD


Translational displacement mag
mm
0.028
0.0252
0.0224
0.0196
0.0168
0.014
0.0112
0.00839
0.00559
0,0028
0
On Boundary

CAD

CAD

Video

Prototype


RobEcolo
Conception de Robots industriels à base de
matériaux à faible impact Ecologique
Contexte

Conclusions

- Objectives of RobEcolo:
  - how to design robots with low environmental impact by using bio-sourced materials
  - how to make them accurate and stiff
- An integrated approach
  - Sensor-based control
  - Optimal design
    - control-based design
    - robust design
- A multidisciplinary project
  - Modeling of wood for robotics
  - Wood machining!!
- A lot of experimental work to be done now
  - Robot commissionning
  - Implementation of controllers
  - Characterization of the robot properties

The team

Permanent researchers

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