Improving the Dynamics Performance of Fast Robot Manipulators

Own results and future challenges

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June 28, 2016

Introduction

Fast Robot Manipulators?

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Fast Robot Manipulators?

In the large majority ⇒ Parallel Robots

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Fast Robot Manipulators?

In the large majority $\Rightarrow$ Parallel Robots

Most of my work is on parallel robots
(but not restricted to!)

Introduction

Why parallel robots?

Known advantages

- high payload-to-weight ratio
- high intrinsic stiffness
- large number of architectures (versatility)
- high acceleration capacities

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No concurrents

Fastest robots

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No concurrents

Fastest robots

- Serial robot: Staübli's FAST Picker (about 10 G)

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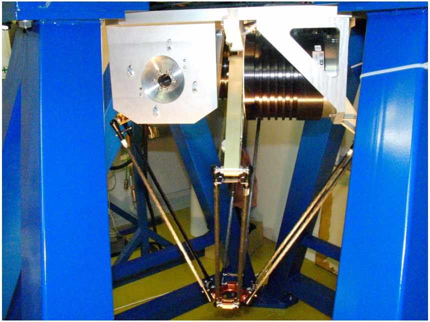
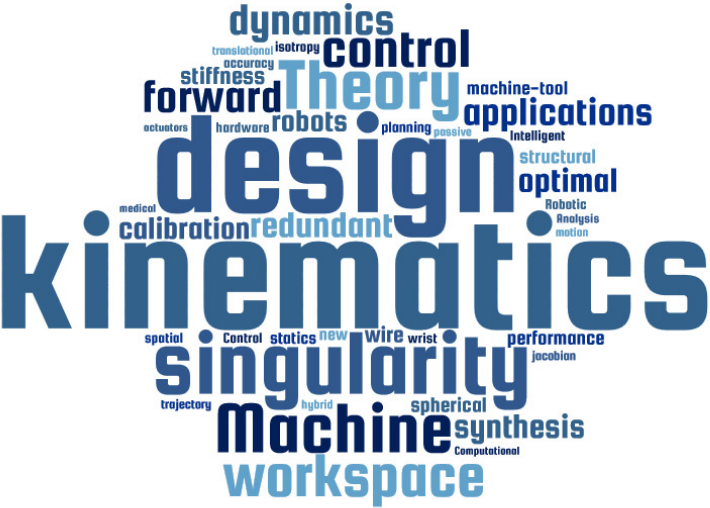


No concurrents

Fastest robots

- Serial robot: Staübli's FAST Picker (about 10 G)
- Parallel Robot: R4 from LIRMM ($>$ 100 G)

Main keywords in articles on parallel robots



Introduction

Few works on dynamics of parallel robots

Is everything done?

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DYNAMICS' NOT DEAD!

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DYNAMICS' NOT DEAD!

- Dynamics vs. accuracy
- Dynamics singularities
- Vibrations
- Dynamics vs. energy consumption
- Dynamics vs. human safety
- Fast robots mounted on mobile, flying, swimming ... robots

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Few works on dynamics of parallel robots

Is everything done?

DYNAMICS' NOT DEAD!

- **Dynamics vs. accuracy**
- **Dynamics singularities**
- **Vibrations**
- Dynamics vs. energy consumption
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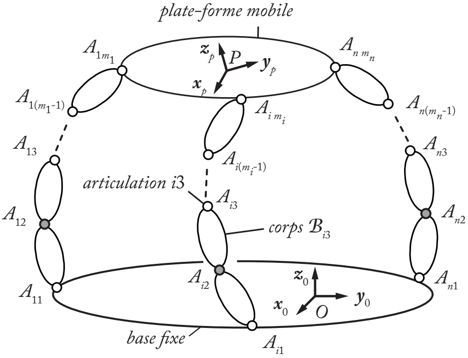
Outline of the presentation

1. Degeneracy conditions of the dynamic model of parallel robots
2. Design and control of high-speed and high-accuracy robots
3. Other works on dynamics
4. Future challenges and conclusions

Degeneracy of the dynamics in Type 2 singularities

Generic parallel robot



Degeneracy of the dynamics in Type 2 singularities

Inverse dynamic model

$$\begin{matrix} \boldsymbol{\tau} = \mathbf{w}_b - \mathbf{B}_p^T \boldsymbol{\lambda} \\ \mathbf{A}_p^T \boldsymbol{\lambda} = \mathbf{w}_p \end{matrix} \quad \text{with} \quad \mathbf{A}_p \dot{\mathbf{x}} + \mathbf{B}_p \dot{\mathbf{q}}_a = \mathbf{0} \Rightarrow \boldsymbol{\tau} = \mathbf{w}_b - \mathbf{B}_p^T \mathbf{A}_p^{-T} \mathbf{w}_p \qquad (1)$$

$\dot{\mathbf{x}}$: derivative of the platform configuration (NOT the platform twist)

$\dot{\mathbf{q}}_a$: active joint velocities

$\mathbf{w}_b = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\mathbf{q}}_a}\right) - \frac{\partial L}{\partial \mathbf{q}_a}$

$\mathbf{w}_p = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\mathbf{x}}}\right) - \frac{\partial L}{\partial \mathbf{x}}$

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Thus,

The dynamic model is proportional to $\frac{1}{\det(\mathbf{A}_p)}$

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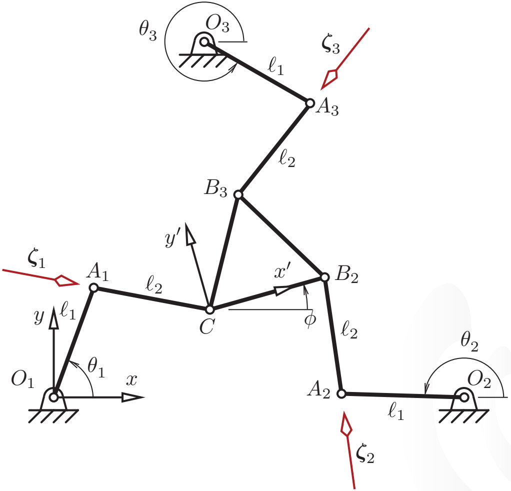
So, if $\det(\mathbf{A}_p) = 0$, (Type 2 sing. [Gosselin & Angeles 1990])

- **Near singularities, $\boldsymbol{\tau} \rightarrow \infty$**
- Dynamic model degeneracy = **Impossible to cross sing.**

Why crossing Type 2 singularities is appealing?



[Bonev 2002]

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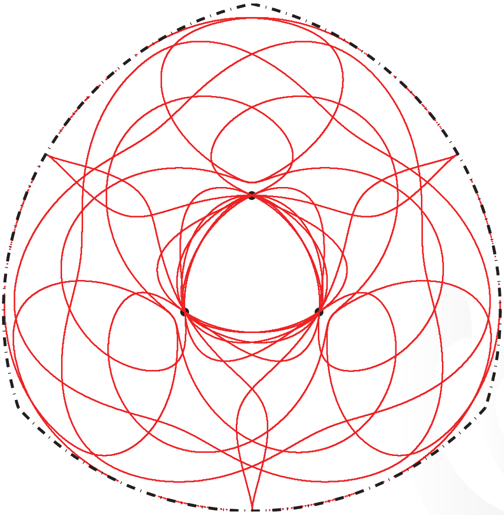

[Bonev 2002]

Degeneracy of the dynamics in Type 2 singularities

Inverse dynamic model

$$\boldsymbol{\tau} = \mathbf{w}_b - \mathbf{B}_p^T \mathbf{A}_p^{-T} \mathbf{w}_p \quad (2)$$

Contribution

Dynamics does not degenerate in Type 2 singularity iff

$$\mathbf{t}_s^T \mathbf{w}_p = 0, \quad (3)$$

$$\text{with } \mathbf{t}_s \text{ defined by } \mathbf{A}_p \mathbf{t}_s = \mathbf{0}, \quad (4)$$

Degeneracy of the dynamics in Type 2 singularities

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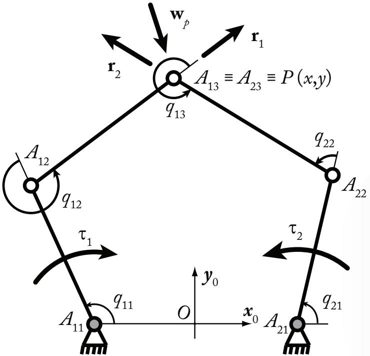
⇒ When the robot cross a Type 2 singularity, the wrenches applied on the platform (by the legs, the inertial effects, gravitation, external efforts) $\mathbf{w}_p$ must be reciprocal to the uncontrollable platform motion $\mathbf{t}_s$

Degeneracy of the dynamics in Type 2 singularities

An illustrative example

In an arbitrary configuration

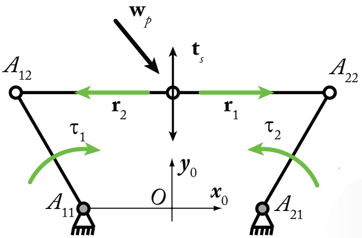


Equilibrium iff $\mathbf{w}_p = \mathbf{r}_1 + \mathbf{r}_2$

Degeneracy of the dynamics in Type 2 singularities

An illustrative example

In singularity



$\mathbf{w}_p = \mathbf{r}_1 + \mathbf{r}_2$ with

- $\mathbf{r}_1 \times \mathbf{r}_2 = \mathbf{0}$
- $\mathbf{t}_s^T \mathbf{r}_1 = \mathbf{t}_s^T \mathbf{r}_2 = 0$ ($\mathbf{t}_s$ uncontrollable motion)

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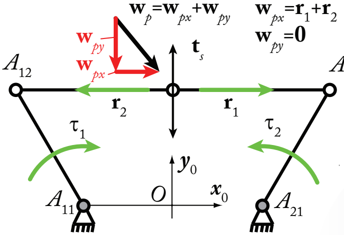

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Problem if $\mathbf{t}_s^T \mathbf{w}_p \neq 0$

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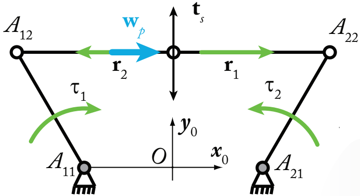

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No problem if $\mathbf{t}_s^T \mathbf{w}_p = 0$

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Trajectories through Type 2 singularities

Require to respect the criterion $\mathbf{t}_s^T \mathbf{w}_p = 0$ in singularity

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Note that:

- $\mathbf{t}_s$ depends on the robot configuration
- $\mathbf{w}_p$ depends on the robot configuration, velocity and acceleration

Degeneracy of the dynamics in Type 2 singularities

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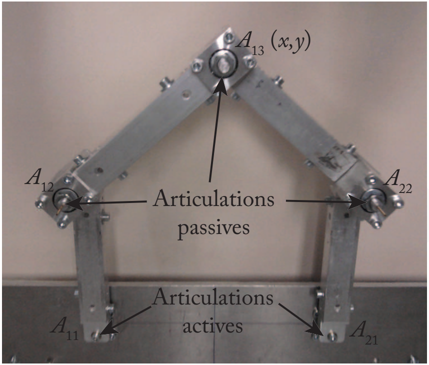

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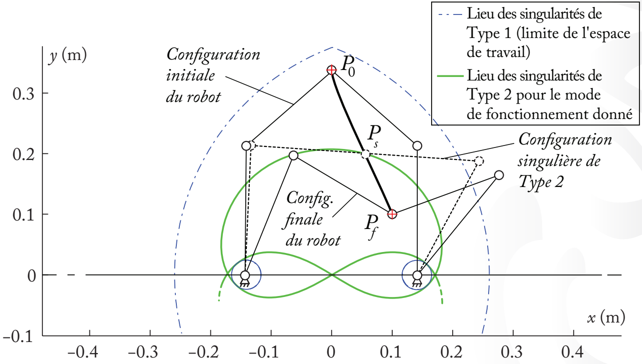

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TRAVERSEE Type 2

Criterion is not respected

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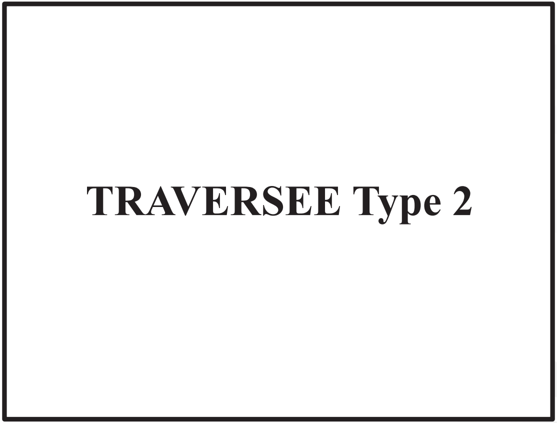

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Degeneracy of the dynamics in Type 2 singularities

Robustness issues

Can be manage through a proper Computed Torque Controller (CTC) [Pagis et al 2015]

Degeneracy of the dynamics in Type 2 singularities

Robustness issues

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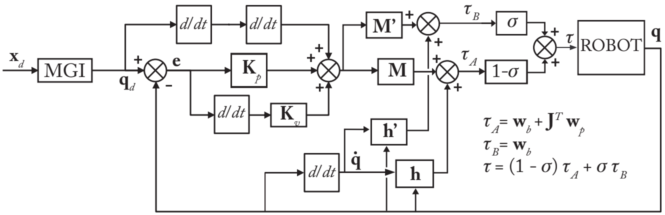
To develop it, we impose a trajectory with $\mathbf{w}_p = \mathbf{0}$ at singularity (respects $\mathbf{t}_s^T \mathbf{w}_p = 0$)



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Degeneracy of the dynamics in Type 2 singularities

Conclusions

- Definition of dynamic model degeneracy conditions...

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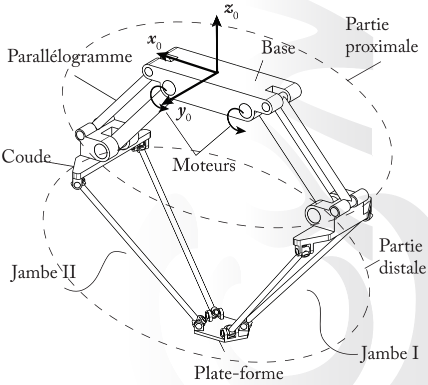
- Future works: Constraint sing. crossing, CDPM

Design / Control of fast and accurate robots

Design of a 2T robot for *pick-and-place* operations

Advantages:

- Intrinsic stiffness
- Smaller number of legs than the Par2



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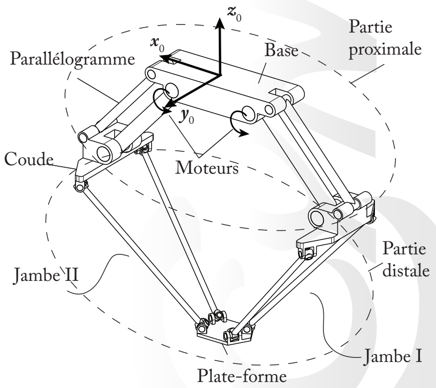

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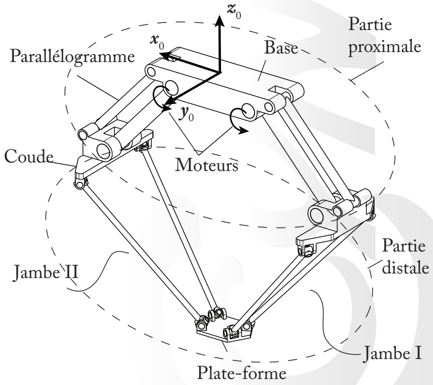
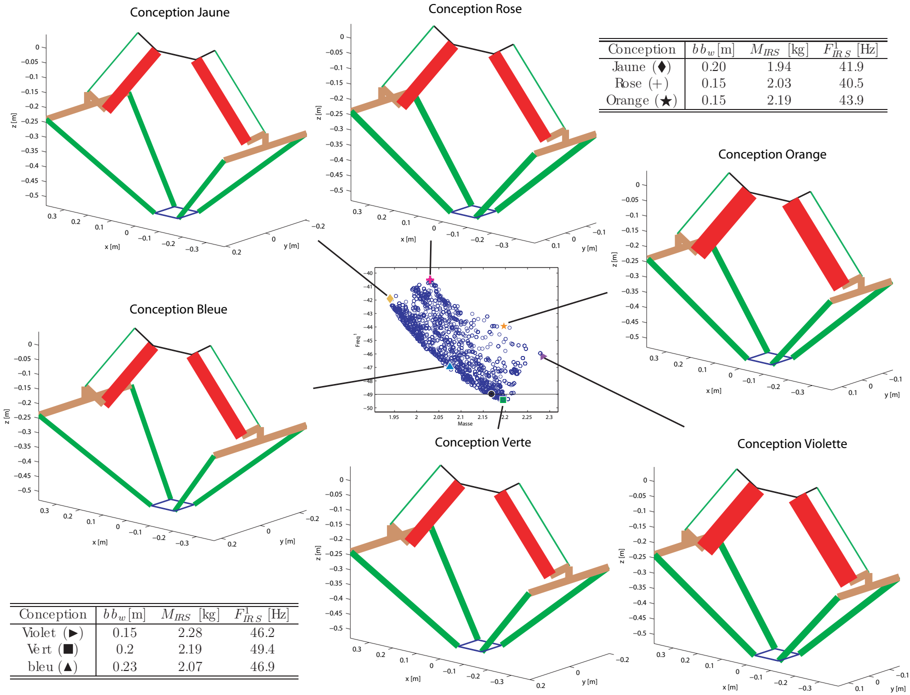
Work done in the scope of the French ANR project ARROW



Design / Control of fast and accurate robots

Specifications

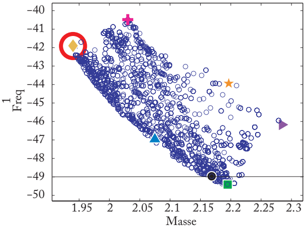
Type of motion	2T 1R
Repeatability ϵ_{lim} in (xOz)	20 μm
Resolution r_{lim}	2 μm
Max. acceleration	20 G
Cycle time	200 ms
Path dimension	25 mm × 300 mm × 25 mm
Regular workspace size	800 mm × 100 mm
Deformation $\delta_{t\,lim}$ under a force $\mathbf{f}_s = [0, 20, 0]$ N and a moment $\mathbf{m}_s = [1, 1, 1]$ N.m	[0.2, 0.2, 0.2] mm, [0.1, 0.1, 0.1] deg
Max. payload (including the embedded motor)	1.5 kg



Conception	bb_w [m]	M_{IRS} [kg]	F^1_{IRS} [Hz]
Jaune (♦)	0.20	1.94	41.9
Rose (+)	0.15	2.03	40.5
Orange (★)	0.15	2.19	43.9

Conception	bb_w [m]	M_{IRS} [kg]	F^1_{IRS} [Hz]
Violet (▶)	0.15	2.28	46.2
Vert (■)	0.2	2.19	49.4
bleu (▲)	0.23	2.07	46.9

Optimisation results



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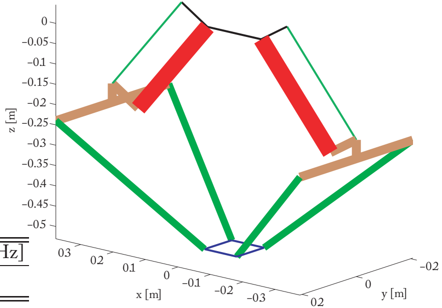
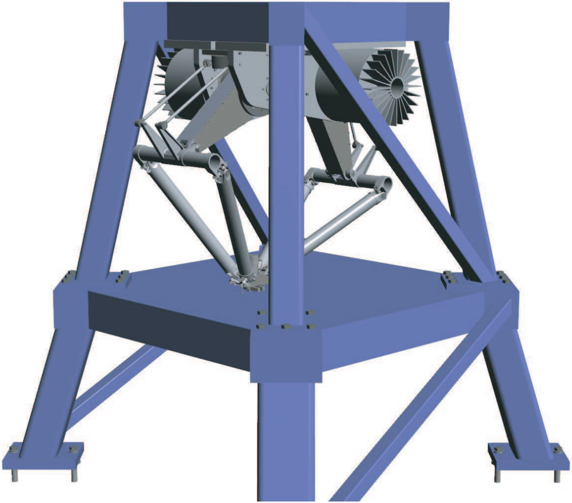


IRSBot-2 prototype



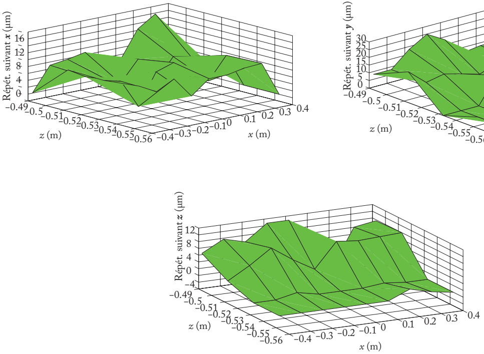
Tecnalia

- $\delta_{ty} < 0.17$ mm
- $f^1_{IRS} = 44.9$ Hz (in the plane)
- $f^2_{IRS} = 55$ Hz (out the plane)

IRSBot-2 prototype

Design / Control of fast and accurate robots

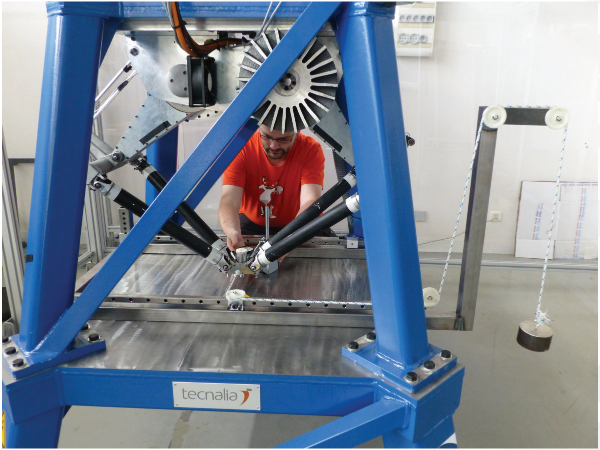
Repeatability performance



30 microns in the dexterous regular workspace

Design / Control of fast and accurate robots

Static deformations



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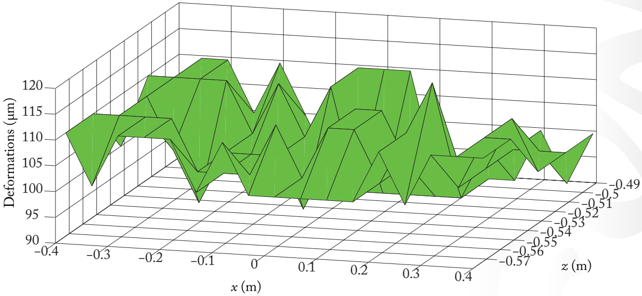
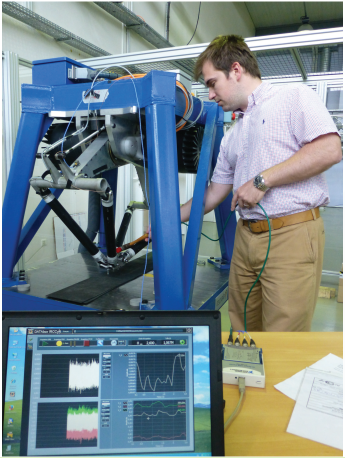


120 microns in the dexterous regular workspace under a load of 20 N along y_0

Design / Control of fast and accurate robots

Natural frequencies



Design / Control of fast and accurate robots

Natural frequencies

Calculées par CAO		Obtenues par sonnage	
Frequency	Displacement mode	Frequency	Displacement mode
45 Hz	Perp. to motion	40±1 Hz	Perp. to motion
53 Hz	Plane of motion	40±1 Hz	Plan of motion
60 Hz	Perp. to motion	48±1 Hz	Perp. to motion

Design / Control of fast and accurate robots

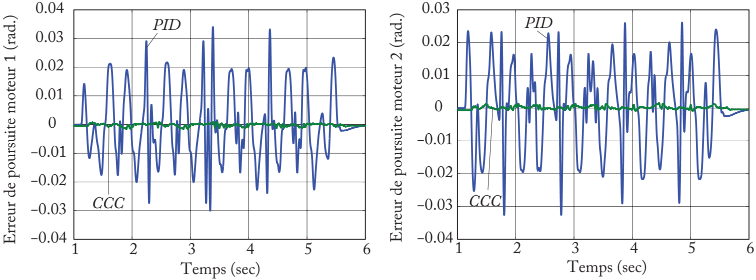
Dynamic performance

TRAVERSEE Type 2

20 G of acceleration, 6 m/s

Design / Control of fast and accurate robots

Dynamic performance



Tracking error divided by 20 between PID and CTC

Design / Control of fast and accurate robots

What is not mentioned

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Ongoing work

- Vibration control

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  - **Sensor-based control**

Design / Control of fast and accurate robots

Vision-based control of fast and accurate robots

Different possible approaches

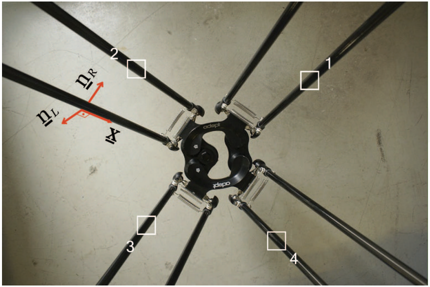
- direct observation of the end-effector [Paccot et al., 2008]

Design / Control of fast and accurate robots

Vision-based control of fast and accurate robots

Different possible approaches

- observation of legs [Özgür et al., 2011]



Design / Control of fast and accurate robots

Vision-based control of fast and accurate robots

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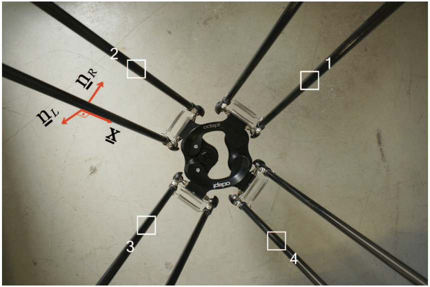

Leg-direction-based visual servoing

Issues / Questions

- the observation of m leg directions ($m < n$) among the n legs is enough,

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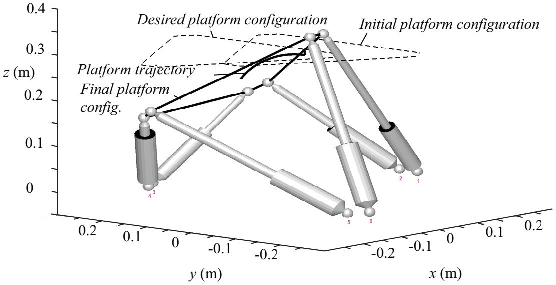

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- convergence problems for the end-effector, even if there is convergence of the leg directions
- existence of local minima
- singularities of the model (between the leg space and the Cartesian space)

Leg-direction-based visual servoing

Possible to answer to these questions thanks to the concept of "Hidden Robot"

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Basic idea

We must understand that, intrinsically, controlling the robot by observing its legs is equivalent to control another architecture

$$\mathbf{e} = \underline{\mathbf{u}} - \underline{\mathbf{u}}_{des} \quad (4)$$

$$\dot{\mathbf{e}} = -\lambda \mathbf{e} \Rightarrow \dot{\underline{\mathbf{u}}} = -\lambda \mathbf{e} \quad (5)$$

$$\boldsymbol{\tau} = -\lambda \mathbf{M}^{T+} \mathbf{e} \Rightarrow \dot{\mathbf{q}} = -\lambda \mathbf{J}_{inv} \mathbf{M}^{T+} \mathbf{e} \quad (6)$$

$$\dot{\underline{\mathbf{u}}} = \mathbf{M}^{T} \boldsymbol{\tau} \quad (7)$$

Leg-direction-based visual servoing

Possible to answer to these questions thanks to the concept of "Hidden Robot"

Basic idea

We must understand that, intrinsically, controlling the robot by observing its legs is equivalent to control another architecture

$$\mathbf{e} = \underline{\mathbf{u}} - \underline{\mathbf{u}}_{des} \tag{4}$$

$$\dot{\mathbf{e}} = -\lambda \mathbf{e} \Rightarrow \dot{\underline{\mathbf{u}}} = -\lambda \mathbf{e} \tag{5}$$

$$\boldsymbol{\tau} = -\lambda \mathbf{M}^{T+}\mathbf{e} \Rightarrow \dot{\mathbf{q}} = -\lambda \mathbf{J}_{inv}\mathbf{M}^{T+}\mathbf{e} \tag{6}$$

$$\dot{\underline{\mathbf{u}}} = \mathbf{M}^{T}\boldsymbol{\tau} \tag{7}$$

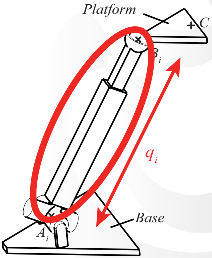
Leg-direction-based visual servoing

Basic idea

We must understand that, intrinsically, controlling the robot by observing its legs is equivalent to control another architecture

Usual encoder-based controller

$\mathbf{q} \Rightarrow \mathbf{x}$ ($\mathbf{q}$: measurement corresponding to the real actuators)



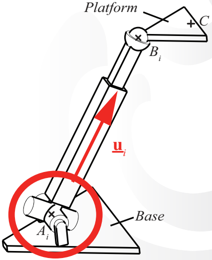
Leg-direction-based visual servoing

Basic idea

We must understand that, intrinsically, controlling the robot by observing its legs is equivalent to control another architecture

Leg-direction-based visual controller

$\underline{\mathbf{u}} \Rightarrow \mathbf{x}$ ($\underline{\mathbf{u}}$: corresponding to the virtual actuators of the hidden robot)



Leg-direction-based visual servoing

Leg-direction-based visual controller

Gough-Stewart platform:

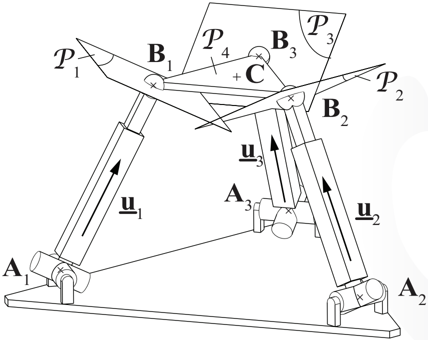
- Real robot ⇒ 6–U$\underline{P}$S

Leg-direction-based visual servoing

Leg-direction-based visual controller

Gough-Stewart platform:

- Real robot ⇒ 6–U<u>P</u>S
- Hidden (virtual) robot ⇒ 3–<u>U</u>PS (case of the minimal observation)

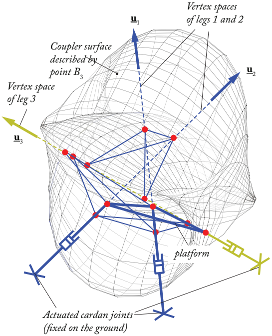


Leg-direction-based visual servoing

Leg-direction-based visual controller

Gough-Stewart platform:

- Real robot ⇒ 6–U$\underline{P}$S
- Hidden (virtual) robot ⇒ 3–$\underline{U}$PS (case of the minimal observation)

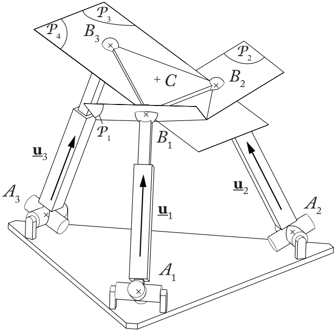


Leg-direction-based visual servoing

Leg-direction-based visual controller

Gough-Stewart platform:

- Real robot ⇒ 6–U<u>P</u>S
- Hidden (virtual) robot ⇒ 3–<u>U</u>PS (case of the minimal observation)



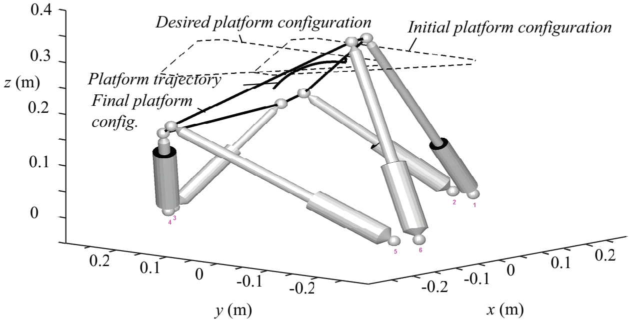
Leg-direction-based visual servoing

By considering this analogy

Leg-direction-based visual servoing

By considering this analogy

⇒ Final (non-desired) platform location ≡ a solution of the FGM of the 3–$\underline{U}$PS robot in the same aspect as the initial configuration



Leg-direction-based visual servoing

By considering this analogy

$\Rightarrow$ Able to explain why the observation of m leg directions ($m < n$) among the n legs is enough

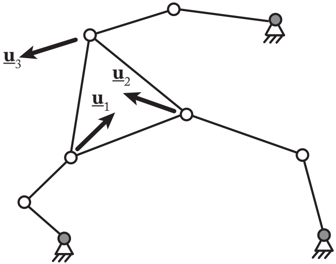
$\Rightarrow$ Find the local minima

$\Rightarrow$ Find the singularities of the model used in the visual servoing

Generalization of the concept and application to different robot classes

Planar robots

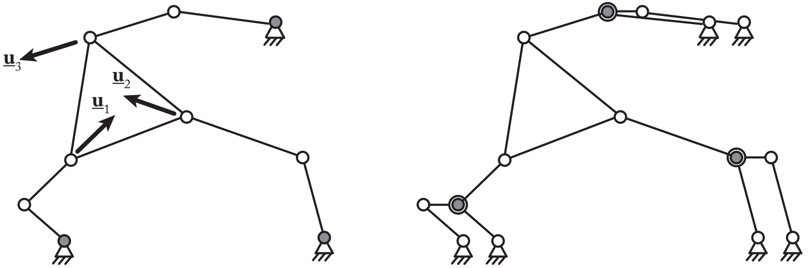
Example of the 3–$\underline{R}$RR robot



Generalization of the concept and application to different robot classes

Planar robots

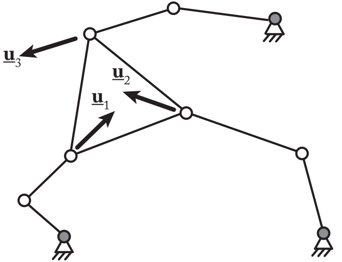
Example of the 3–RRR robot

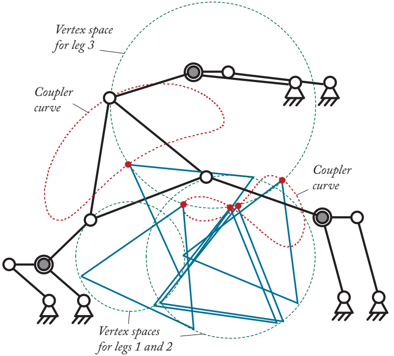


Generalization of the concept and application to different robot classes

Planar robots

Example of the 3–RRR robot

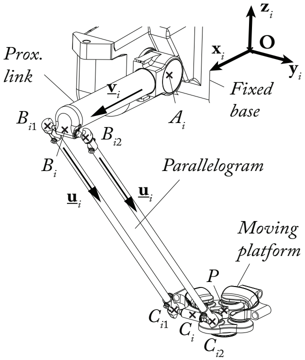




Generalization of the concept and application to different robot classes

Spatial robots

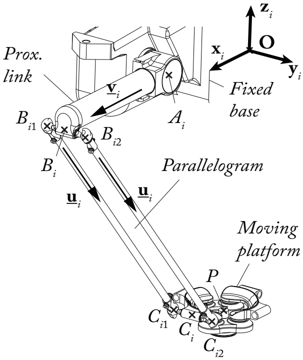
Example of the Adept Quattro

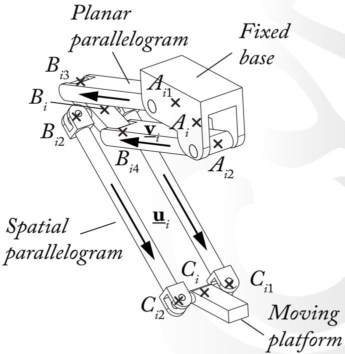


Generalization of the concept and application to different robot classes

Spatial robots

Example of the Adept Quattro

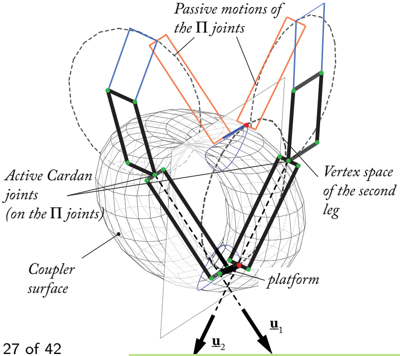


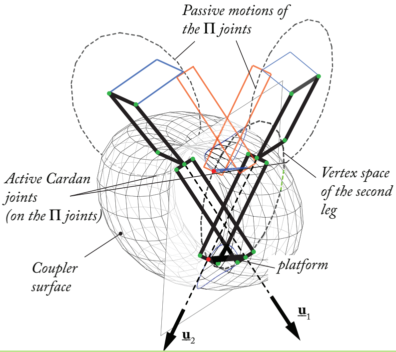


Generalization of the concept and application to different robot classes

Spatial robots

Example of the Adept Quattro

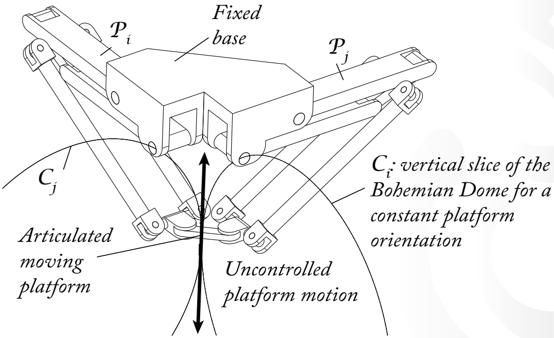




Generalization of the concept and application to different robot classes

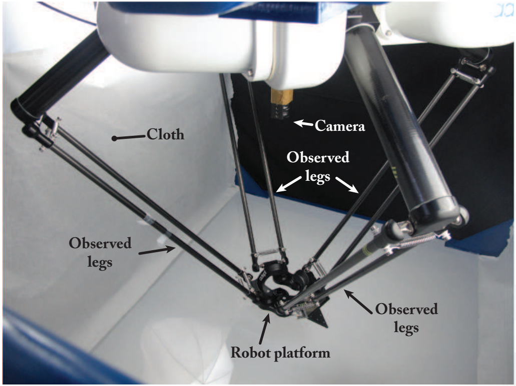
Spatial robots

Example of the Adept Quattro



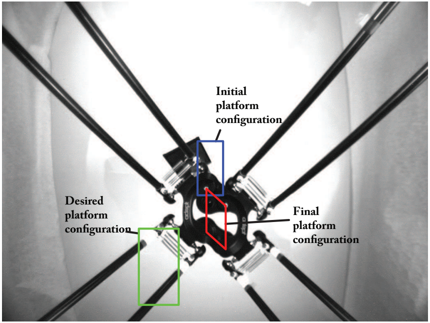
Generalization of the concept and application to different robot classes

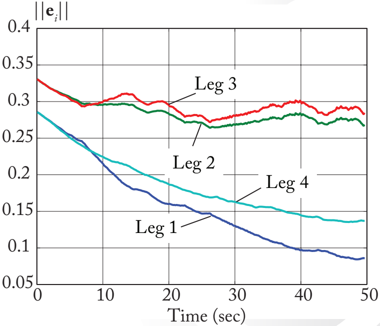
Experimental validation



Generalization of the concept and application to different robot classes

Experimental validation





Use of the concept of hidden robot for the controllability analysis

Definition of four main classes of robots for leg-direction-based controllers

Cl 1: Robots which are not controllable

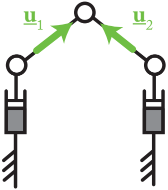
Cl 2: Robots which are partially controllable in their whole workspace

Cl 3: Robots which are fully controllable in their whole workspace

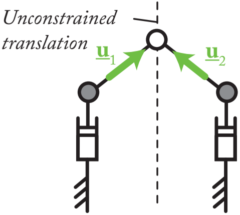
Cl 4: Robots which becomes controllable by using additional measurements

Use of the concept of hidden robot for the controllability analysis

Class 1: Robots which are not controllable



A *PRRRP* robot

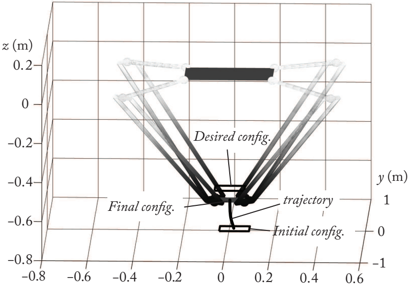


Hidden robot:
a *PRRRP* robot

Use of the concept of hidden robot for the controllability analysis

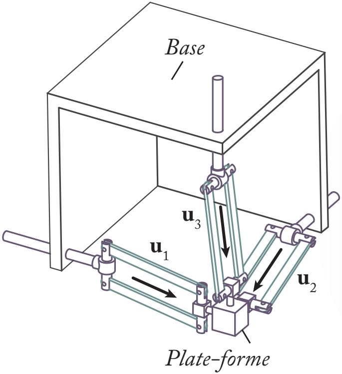
Class 2: Robots which are partially controllable in their whole workspace

⇒ because singularities of the hidden robot **always** divide the workspace into several aspects (unconnected areas)



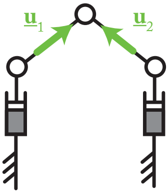
Use of the concept of hidden robot for the controllability analysis

Class 3: Robots which are fully controllable in their whole workspace



Use of the concept of hidden robot for the controllability analysis

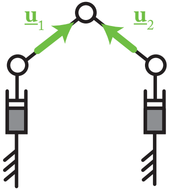
Class 4: Robots which becomes controllable by using additional measurements



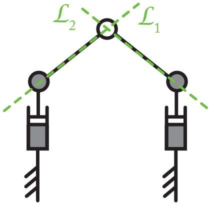
A *P̲RRRP̲* robot

Use of the concept of hidden robot for the controllability analysis

Class 4: Robots which becomes controllable by using additional measurements



A $\underline{P}RRR\underline{P}$ robot



Hidden robot:
a $\underline{P}R\underline{R}\underline{R}\underline{P}$ robot

Design / Control of fast and accurate robots

Conclusions

- New “spatial” 2T robot architecture

Design / Control of fast and accurate robots

Conclusions

- New “spatial” 2T robot architecture
- Optimal design methodology for fast and accurate robots

Design / Control of fast and accurate robots

Conclusions

- New "spatial" 2T robot architecture
- Optimal design methodology for fast and accurate robots
- Improving the accuracy of high-speed robots

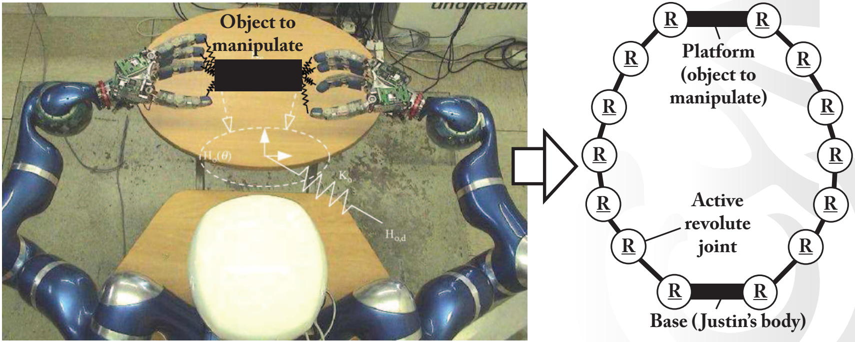
Design / Control of fast and accurate robots

Conclusions

- New "spatial" 2T robot architecture
- Optimal design methodology for fast and accurate robots
- Improving the accuracy of high-speed robots
- Definition of a tool for understanding the mapping characteristics of some visual servoing

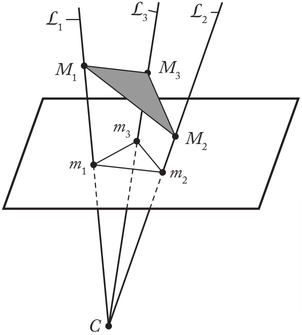
Ongoing and future works

Use of the concept of hidden robot for the visual servoing of multi-arm robots



Ongoing and future works

Use of the concept of hidden robot for the visual servoing of geometric primitives



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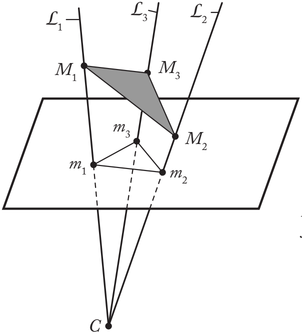

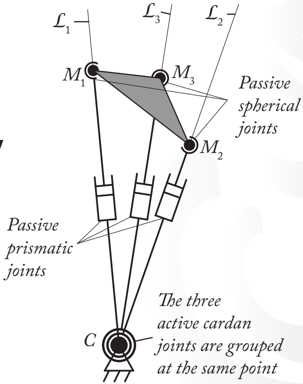

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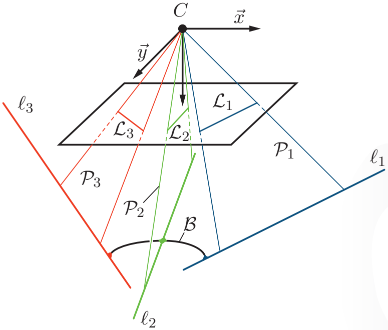
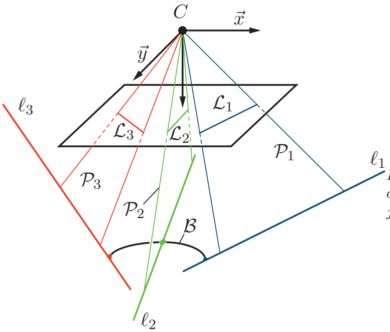
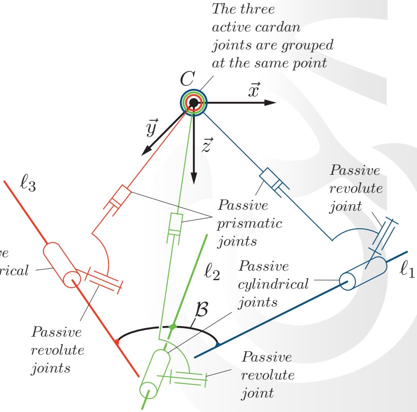


Ongoing and future works

Use of the concept of hidden robot for the visual servoing of geometric primitives





Ongoing and future works

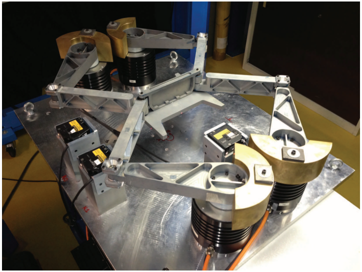
Use of the concept of hidden robot for control-based design

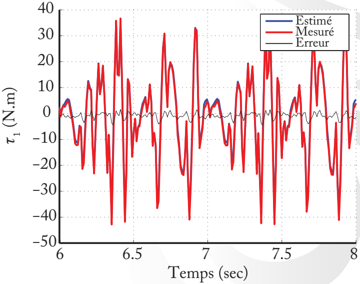
Summary of other past works

Identification of dynamic parameters

Methodologies for the identification of dynamic parameters

- including the driving gains
- for overactuated robots

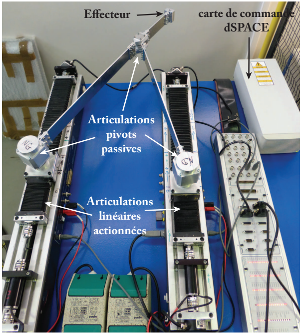


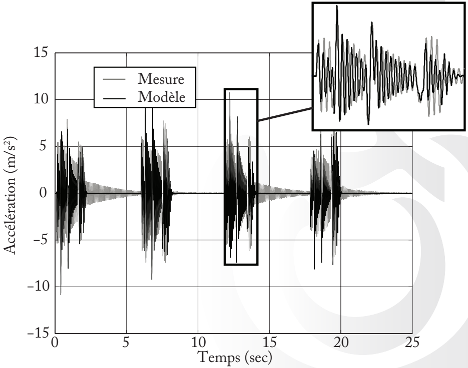


Summary of other past works

Elastodynamic modelling

Systematic / automatic procedure for the symbolic computation of the elastodynamic model of parallel robots

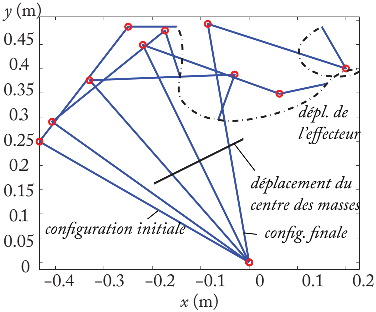


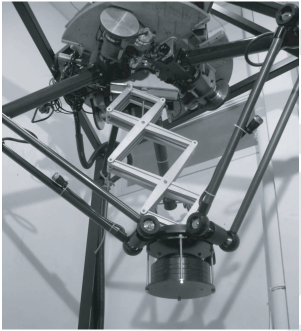


Summary of other past works

Balancing techniques

- dynamics (by optimal design, by optimal motion planning, etc.)
- statics (for high-load carrying robots)



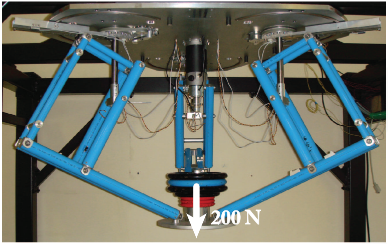


Summary of other past works

Design of robots for high-load carrying

New parallel robot families with decoupled motions between

- planar platform motions
- vertical platform translations



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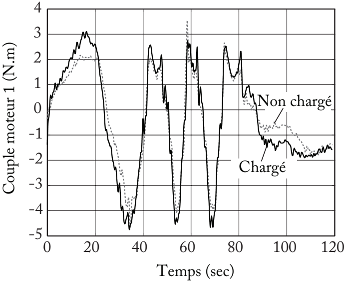
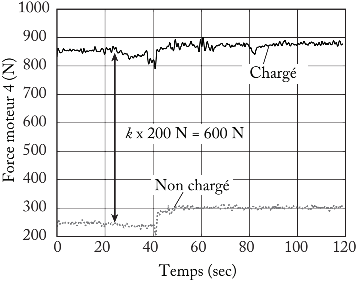




Next challenges

Flying parallel robots

Interests:

- Sharing the load
- Rigid links vs cables ⇒ work also in compression (apply forces on the environment)

Next challenges

Flying parallel robots

Keypoints:

- Management of overconstraint (relative motion between drones = 2 dof)
- Dynamic reconfiguration

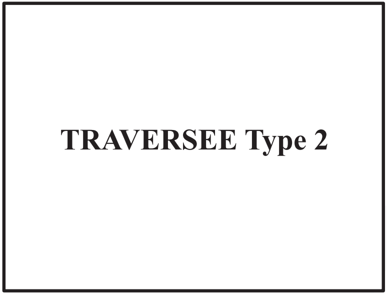
Next challenges

Flying parallel robots

PhD Thesis of Damien Six (2015 – xxxx)

Next challenges

Drastic energy consumption reduction of high-speed robots

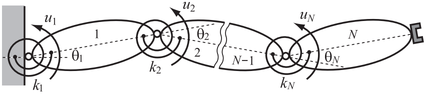


- High energy consumption
- No “relevant” solution

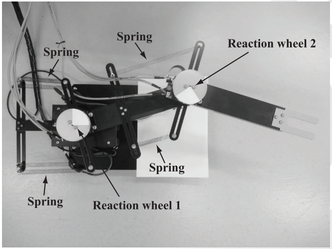
Next challenges

Drastic energy consumption reduction of high-speed robots

- A first step made in that direction via the use of springs



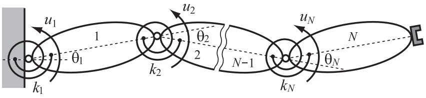
[Uemura et al. 2011]
[Iwamura et al. 2016]



Next challenges

Drastic energy consumption reduction of high-speed robots

- A first step made in that direction via the use of springs
- But
  - "Big" issues of accuracy
  - Just for few trajectories
  - Slow motions (cycle times > 10 sec)



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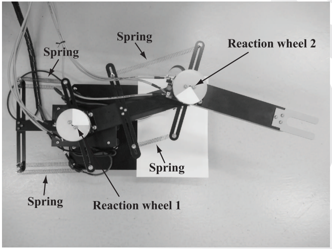


Next challenges

Drastic energy consumption reduction of high-speed robots

PhD Thesis of Rafael Balderas Hill (2016 ??– xxxx)

Next challenges

Design of a lightweight fast manipulator mounted on drones for grasping of moving objects

TRAVERSEE Type 2

Next challenges

Design of a lightweight fast manipulator mounted on drones for grasping of moving objects

Do the same with a manipulator mounted on a drone

- Issues of energy consumption
- Issues of drone stability when the manipulator is moving (at high speed)
- Issues of drone payload capacity

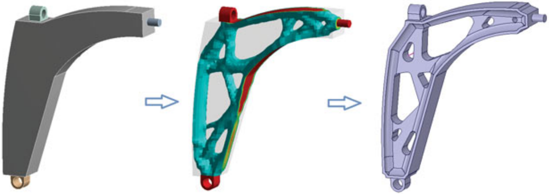
Next challenges

Design of a lightweight fast manipulator mounted on drones for grasping of moving objects

Work both on

⇒ Novel actuation systems (small powerless actuators vs high acceleration)

⇒ Topological optimization of robots



Next challenges

Design of a lightweight fast manipulator mounted on drones for grasping of moving objects

ANR DOS-COM ?? (IRCCyN, Heudiasyc, Gipsa-lab)

Next challenges

Other next works

- Eco-design of robots
- Singularity analysis for generic sensor-based controllers
- Control-based design

To conclude

Two messages to leave

- Dynamics' not dead!
  (Especially for the design of fast robot manipulators)

To conclude

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- Dynamics' not dead!
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- Mechanics' not dead!

To conclude

Two messages to leave

- Dynamics' not dead!
  (Especially for the design of fast robot manipulators)
- Mechanics' not dead!
  - Control cannot solve all issues

To conclude

Two messages to leave

- Dynamics' not dead!
  (Especially for the design of fast robot manipulators)
- Mechanics' not dead!
  - Control cannot solve all issues
  - **Many tools used by mechanical engineers can solve tricky issues of control engineering community**

These works were done in collaboration with

Permanent researchers

IRCCyN

- P. Martinet, M. Gautier, S. Caro, V. Arakelian, A. Chriette, W. Khalil

Other labs

- N. Bouton (SIGMA, ex IFMA), F. Chaumette (Irisa)

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PhD students

- Past: C. Germain, G. Pagis, V. Rosenzveig
- Current: D. Six, L. Kaci, A. Koessler