ICRA16 Workshop on
Application of the theoretical background in Parallel Robotics to other research areas

Advanced control of parallel robots and its extension to other research fields
The concept of "Hidden Robot"

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  - Illustrations

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  - *Controllability analysis*
  - *Extension of the concept*
  - *Conclusion*

Part I Vision Based Control

- Introduction
- Vision Based Control
- Application to Parallel Robot
- Illustrations

Motivations:

Use exteroceptive sensors which allow to measure directly in task space

Explore the potentialities of vision sensor (but not only)

Try to answer some questions:
- What is the real state for a complex system ?
- What is the real state for a parallel robot?
- Is it possible to control by vision only in kinematic/dynamic?
- Is it accurate enough?
- Does it work in a large workspace?

Can we define a generic and integrated formalism for **M**odelling/**I**dentification and **C**ontrol (MICMAC) for complex **MAC**hines (Parallel robots)? In kinematic ? … Dynamic?

Research done at LASMEA *2000-2011* (Pascal Institute in Clermont-Fd)

Nicolas Andreff

PhD

Pierre Renaud

Tej Dallej

Erol Özgür

Ludovic Magerand

Arnaud Marchadier
Master

Flavien Paccot

Redwan Dahmouche

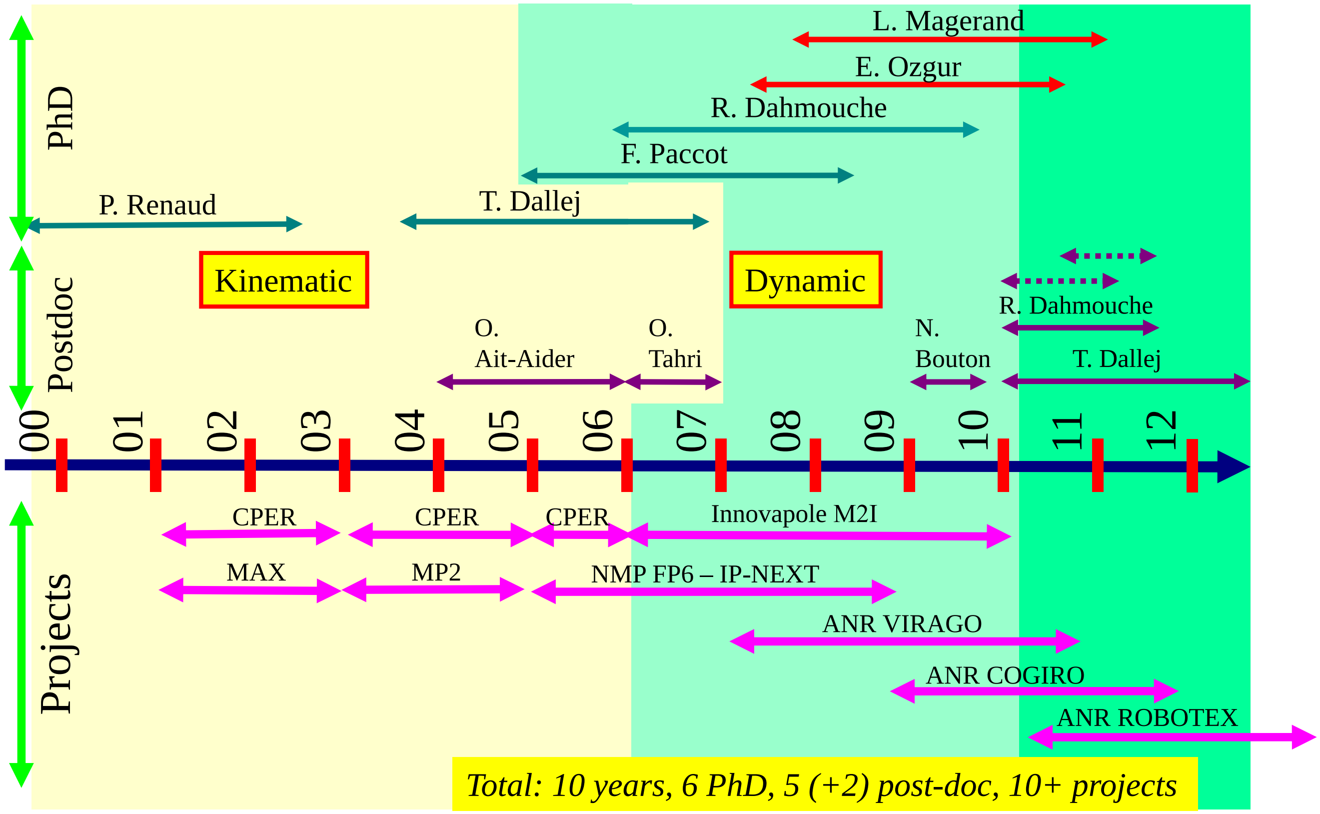
PostDoc

Omar Ait-Aider

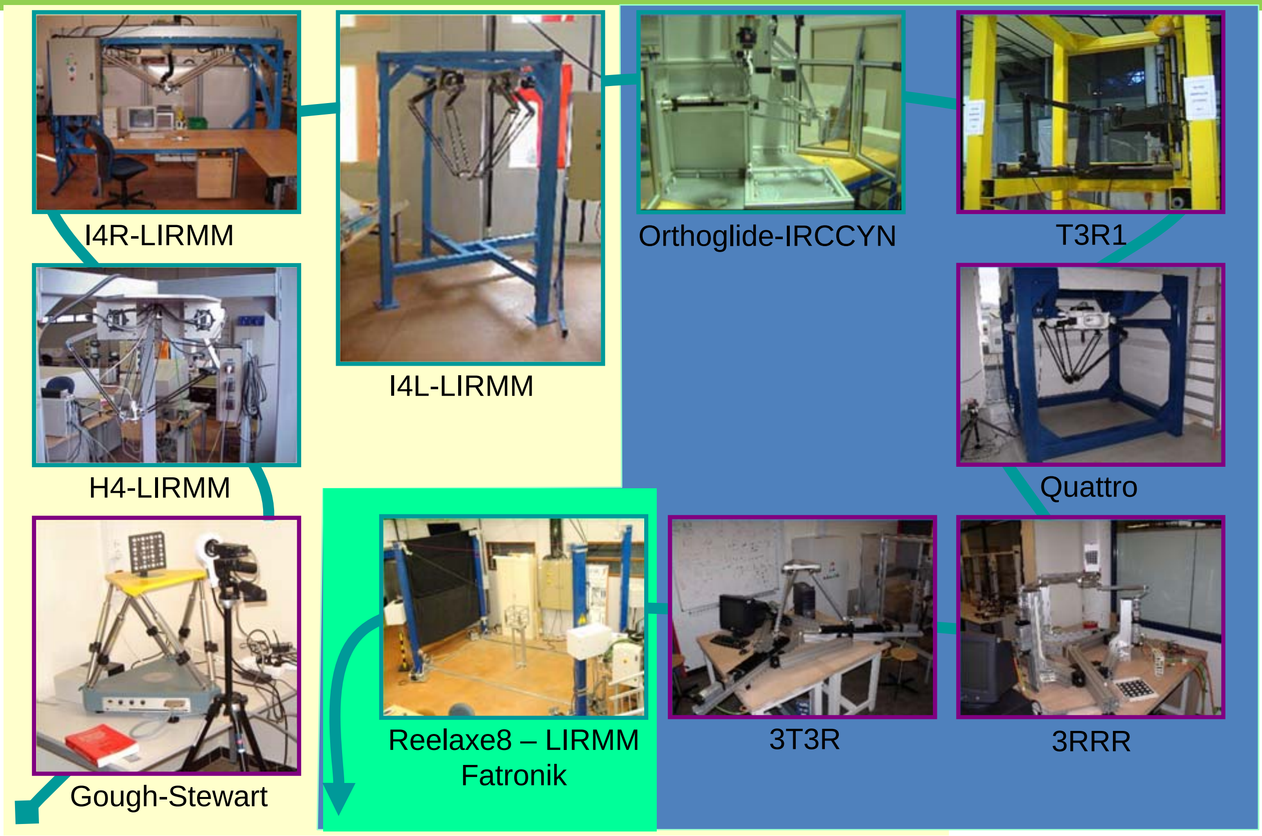
Omar Tahri

Nicolas Bouton

Tej Dallej



Total: 10 years, 6 PhD, 5 (+2) post-doc, 10+ projects



I4R-LIRMM

I4L-LIRMM

Orthoglide-IRCCYN

T3R1

H4-LIRMM

Quattro

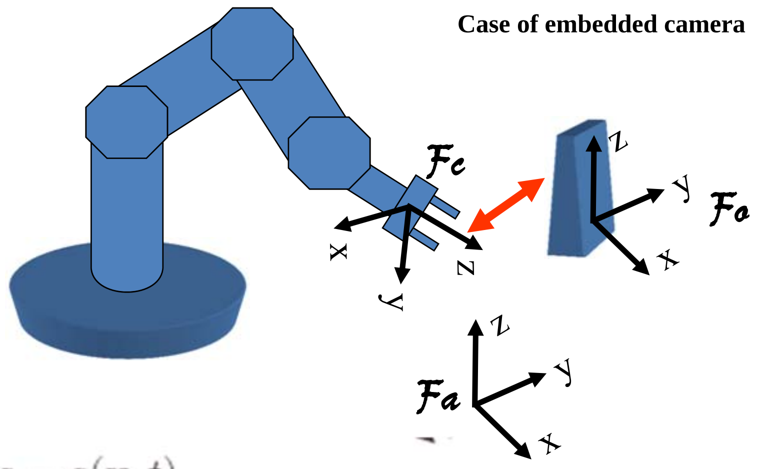
Gough-Stewart

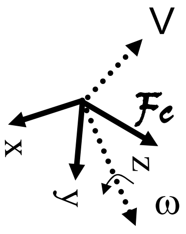
Reelaxe8 – LIRMM
Fatronik

3T3R

3RRR

Case of embedded camera





x : 3D pose

$$\mathbf{s} = \mathbf{s}(\mathbf{x}, t)$$

Interaction matrix

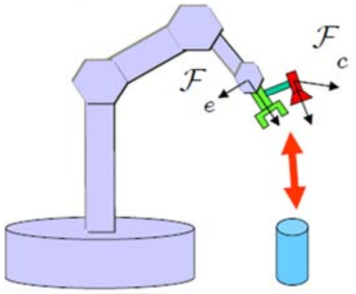
If (fixed object) $\frac{\partial \mathbf{s}}{\partial t} = 0$

$$\dot{\mathbf{s}} = \frac{\partial \mathbf{s}}{\partial \mathbf{x}}\frac{d\mathbf{x}}{dt} + \frac{\partial \mathbf{s}}{\partial t} \Rightarrow \dot{\mathbf{s}} = \mathbf{L}_s \mathbf{v} + \frac{\partial \mathbf{s}}{\partial t}$$

$$\Downarrow$$

$$\dot{\mathbf{s}} = \mathbf{L}_s \mathbf{v}$$

Embedded camera (Eye in hand)



$$L_s$$

★ $\mathcal{F}_c$ Camera frame

★ $\mathcal{F}_e$ End effector frame

$$\dot{s} = L_s v$$

Camera intrinsic parameters In $\mathcal{F}_c$

$$v = -\lambda L_s^{+}(s - s^*)$$

$$\dot{x} = L_x v_e$$

$$v_e = {}^{e}V\, v$$

Camera extrinsic parameters

$$\dot{q} = J(q)^{-1}\, L_x\, v_e = J(q)^{-1}\, L_x\, {}^{e}V\, v$$

Robot jacobian expressed in $\mathcal{F}_e$

Classical Visual servoing concentrates on modelling the interaction between

- Embedded sensor and environment (case of Eye In Hand)
- Gripper and object (case of Eye to Hand)

S can be a feature of different nature : 3D/2D/Hybrid

which

- characterizes the interaction with the environment (relative situation between the end effector and the environment)
- don't characterize any the internal state of the robot

Generally, we define a task error,

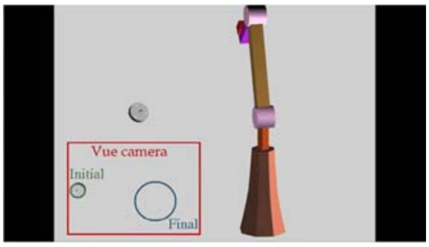
and we impose an exponential decrease of the error which gives a proportional control law

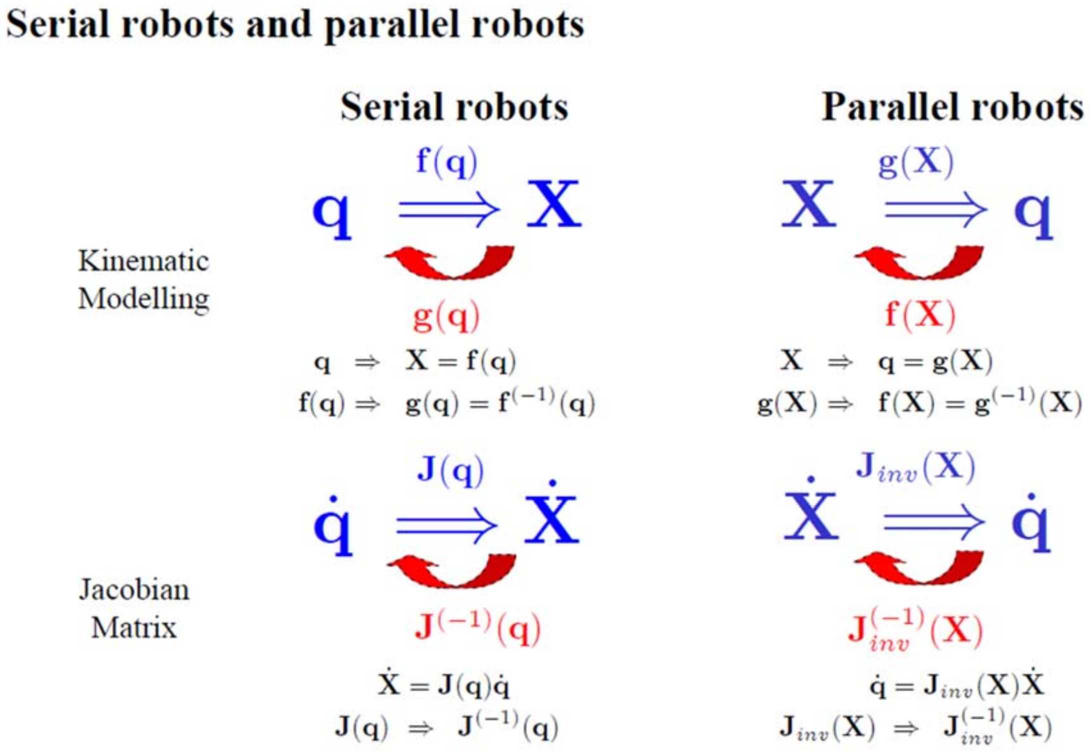
$$\dot{\mathbf{s}} = \mathbf{L}_s \mathbf{v}$$
$$\mathbf{e} = C(\mathbf{s}(t) - \mathbf{s}^*)$$
$$\dot{\mathbf{e}} = -\lambda \mathbf{e}$$
$$\mathbf{v} = -\lambda \mathbf{e}$$
$$\mathbf{v} = -\lambda \mathbf{L}_s^+ (\mathbf{s}(t) - \mathbf{s}^*)$$

e must be a diffeomorphism with the state of the system

L^+ must be not singular with no degenerated cases

(s-s*) must be not in the kernel of L^+ (case of local minima)





Serial robots and parallel robots

Serial robots

Parallel robots

Kinematic Modelling

$$\begin{tikzcd} \mathbf{q} \arrow[r, Rightarrow, "\mathbf{f}(\mathbf{q})"] & \mathbf{X} \arrow[l, bend left, "\mathbf{g}(\mathbf{q})"] \end{tikzcd}$$

$\mathbf{q} \Rightarrow \mathbf{X} = \mathbf{f}(\mathbf{q})$

$\mathbf{f}(\mathbf{q}) \Rightarrow \mathbf{g}(\mathbf{q}) = \mathbf{f}^{(-1)}(\mathbf{q})$

$$\begin{tikzcd} \mathbf{X} \arrow[r, Rightarrow, "\mathbf{g}(\mathbf{X})"] & \mathbf{q} \arrow[l, bend left, "\mathbf{f}(\mathbf{X})"] \end{tikzcd}$$

$\mathbf{X} \Rightarrow \mathbf{q} = \mathbf{g}(\mathbf{X})$

$\mathbf{g}(\mathbf{X}) \Rightarrow \mathbf{f}(\mathbf{X}) = \mathbf{g}^{(-1)}(\mathbf{X})$

Jacobian Matrix

$$\begin{tikzcd} \dot{\mathbf{q}} \arrow[r, Rightarrow, "\mathbf{J}(\mathbf{q})"] & \dot{\mathbf{X}} \arrow[l, bend left, "\mathbf{J}^{(-1)}(\mathbf{q})"] \end{tikzcd}$$

$\dot{\mathbf{X}} = \mathbf{J}(\mathbf{q})\dot{\mathbf{q}}$

$\mathbf{J}(\mathbf{q}) \Rightarrow \mathbf{J}^{(-1)}(\mathbf{q})$

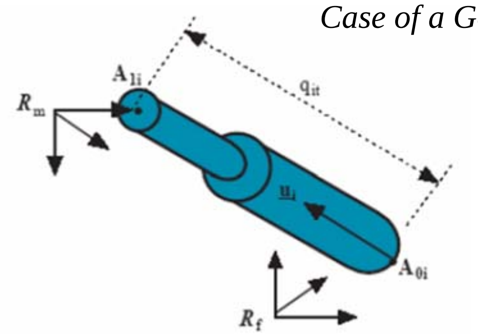
$$\begin{tikzcd} \dot{\mathbf{X}} \arrow[r, Rightarrow, "\mathbf{J}_{inv}(\mathbf{X})"] & \dot{\mathbf{q}} \arrow[l, bend left, "\mathbf{J}_{inv}^{(-1)}(\mathbf{X})"] \end{tikzcd}$$

$\dot{\mathbf{q}} = \mathbf{J}_{inv}(\mathbf{X})\dot{\mathbf{X}}$

$\mathbf{J}_{inv}(\mathbf{X}) \Rightarrow \mathbf{J}_{inv}^{(-1)}(\mathbf{X})$

Kinematic Vision-based control using leg observation

Case of a Gough Stewart platform



$$\dot q = {}^m D_m^{inv}\,.{}^m\tau_m \qquad {}^m D_m^{inv} = \begin{pmatrix} {}^m\underline{u}_1^T & {}^mA_{01} \times {}^m\underline{u}_1{}^T \\ {}^m\underline{u}_2^T & {}^mA_{02} \times {}^m\underline{u}_2{}^T \\ \vdots & \vdots \\ {}^m\underline{u}_6^T & {}^mA_{06} \times {}^m\underline{u}_6{}^T \end{pmatrix}$$

$$ {}^m\dot{\underline{u}}_i = M_i^T\,{}^m\tau_m$$

$$M_i^T = -\frac{1}{q_i}\left(I_3 - {}^m\underline{u}_i{}^m\underline{u}_i^T\right)\left[I_3 \quad -[{}^mA_{0i}]_\times\right]$$

$\mathbf{M}_i^T$ is obviously of rank 2

$$\begin{aligned} e_i &= {}^m\underline{u}_i \times {}^m\underline{u}_{di} \\ &= -{}^m\underline{u}_{di} \times {}^m\underline{u}_i \\ &= [{}^m\underline{u}_{di}]_\times^m\,\underline{u}_i \end{aligned}$$

$$\begin{aligned} \dot e_i &= -[{}^m\underline{u}_{di}]_\times\,.{}^m\,\dot{\underline{u}}_i \\ &= -[{}^m\underline{u}_{di}]_\times\,M_i^T\,{}^m\tau_m \end{aligned}$$

$$E = (\mathbf{e}_1^T, \dots, \mathbf{e}_6^T)^T$$

$$N_i^T = -[{}^m\underline{u}_{di}]_\times\,M_i^T \text{ and } N^T = (N_1, \dots, N_6)^T$$

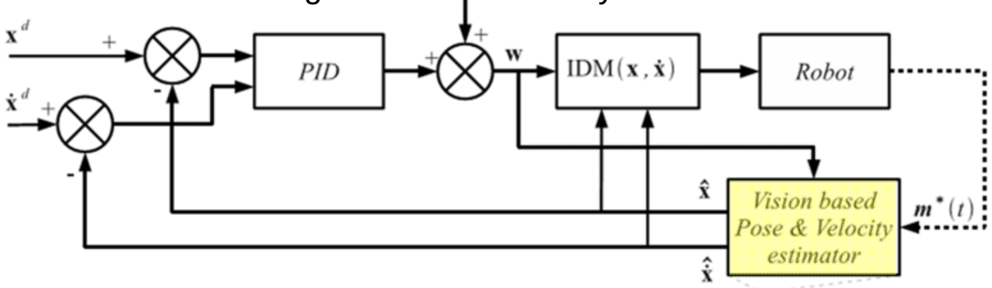
$$\dot E = -\lambda E$$

$$\dot q = -\lambda\,{}^m D_m^{inv}\,{N^T}^+ E$$

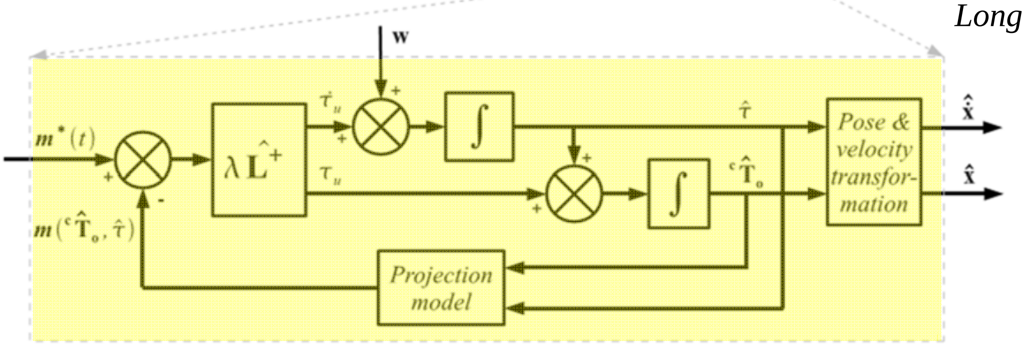
Dynamic Cartesian Based control

[Dahmouche10,12]

Virtual visual servoing for Pose/ Velocity estimation



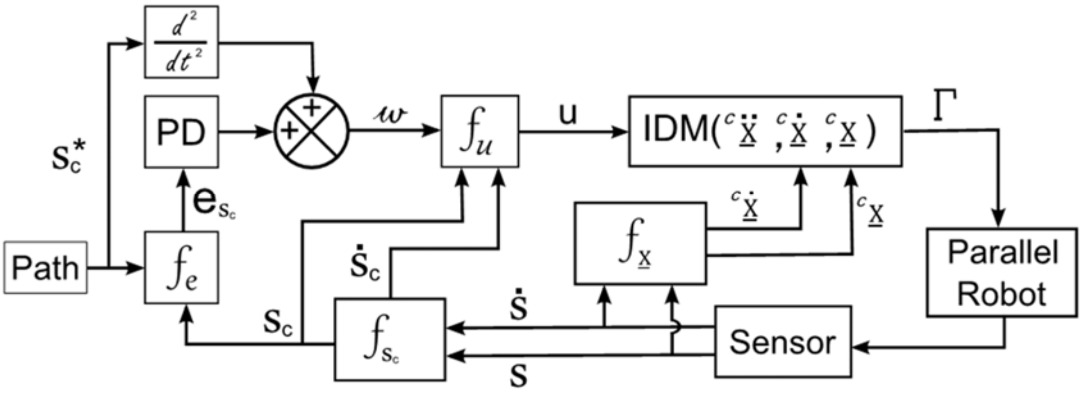
[Ait-Aider06] ECCV06
Longuet Higgins Award



Dynamic Sensor Based Control

[Özgür10]

Generic Control Space



- ➢ CTC* in the legs direction space (LS-CTC) $\mathbf{u}, \dot{\mathbf{u}}$
- ➢ CTC* in cartesian space (CS-CTC) $\mathbf{X}, \dot{\mathbf{X}}$
- ➢ CTC* in image space (Edges) (ES-CTC) $\mathbf{n}, \dot{\mathbf{n}}$ [Özgür11]

$$\mathbf{e} = f_e(\mathbf{s}^*, \mathbf{s}) = \mathbf{s}^* - \mathbf{s}$$

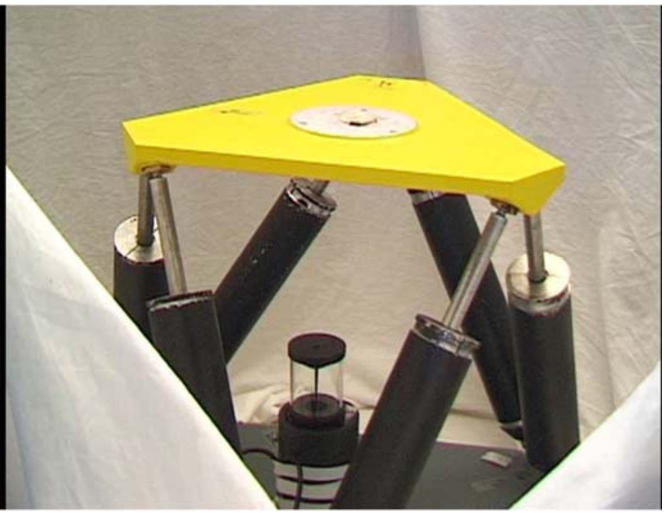
$$\mathbf{u} = f_u(\mathbf{L}_s,\ \dot{\mathbf{L}}_s, \dot{\mathbf{s}}, \omega) = \dot{\mathbf{L}}_s\dot{\mathbf{s}} + \mathbf{L}_s\,\omega$$

**CTC : Computed Torque control*

Kinematic Vision Based Control of Gough Stewart Platform

[Andreff05]

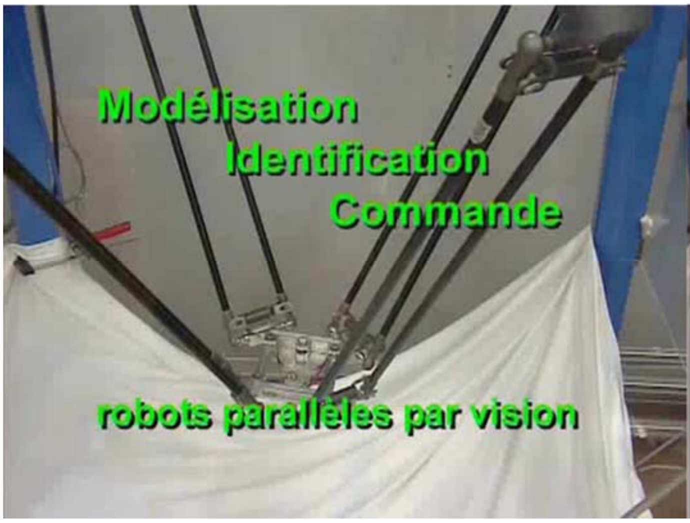
[Tahri07]



Control of parallel robot using legs observation

Kinematic Vision Based Control of Gough Stewart Platform

[Dalle06]



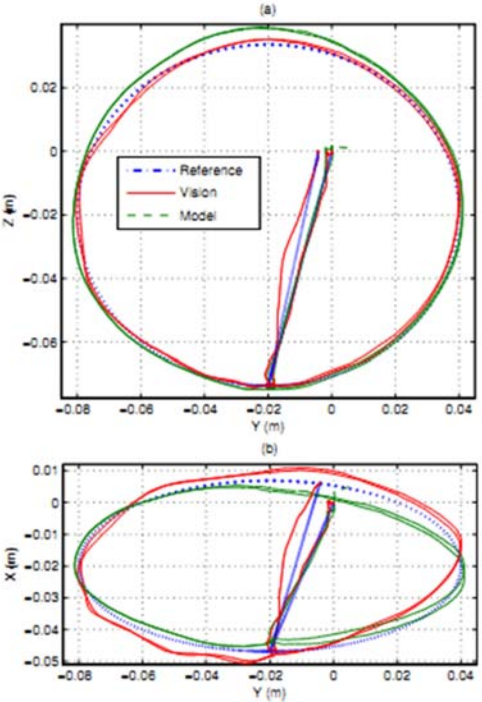
[Dallej06]

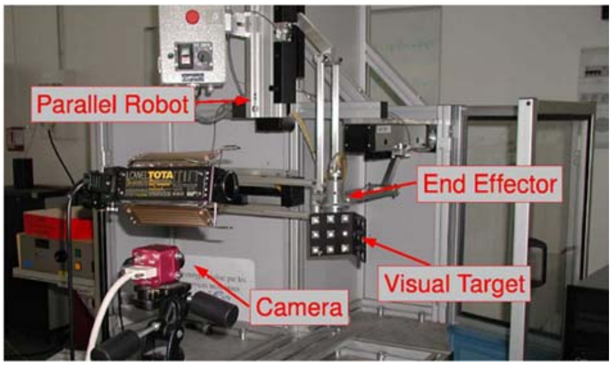
Control of parallel robot using legs observation

Dynamic Cartesian Based control

[Dahmouche10]

Dynamic control of orthoglide at 400Hz (Acquisition 4khz, CMOS Camera)



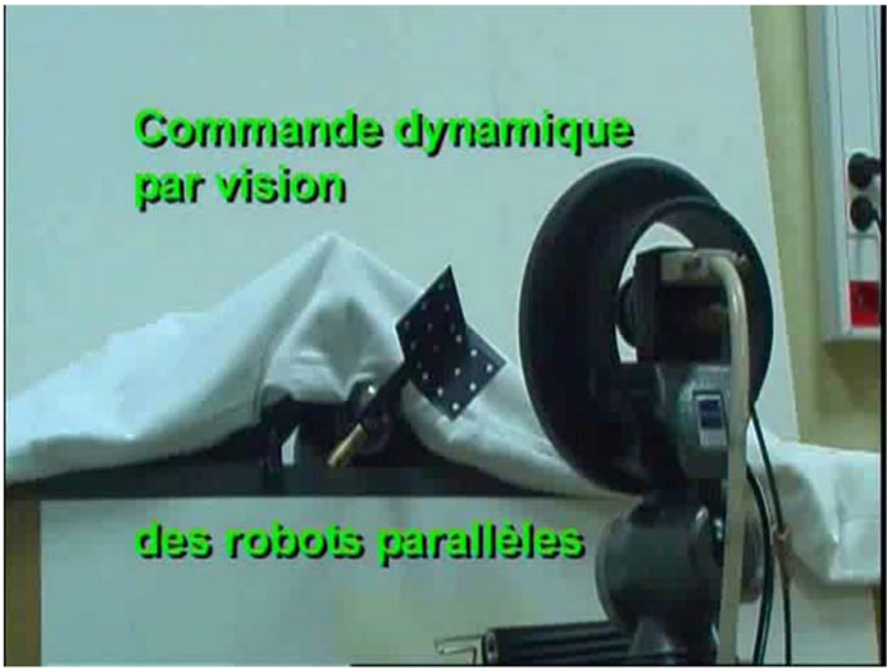


First time that we show that Dynamics Vision Based Control is better than Dymanics Model Based Control

Dynamic Cartesian Based control

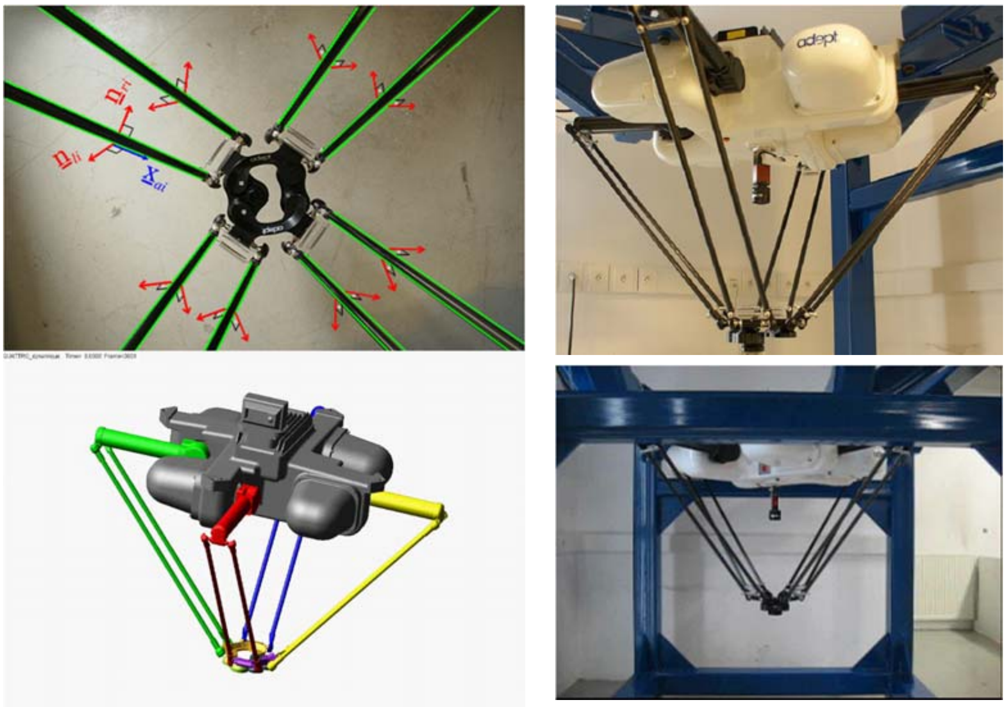
[Dahmouche10]

Dynamic control of orthoglide at 400Hz (Acquisition 4khz, CMOS Camera)



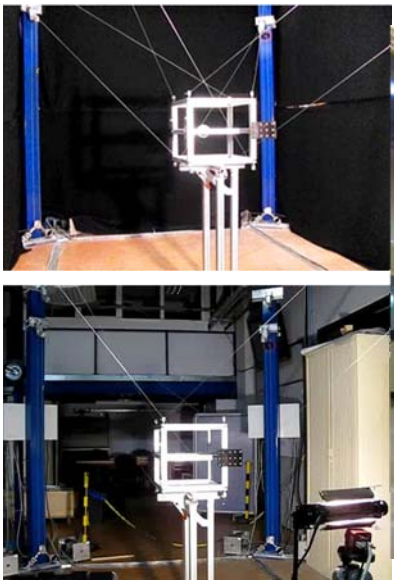
Dynamic Vision Based Control of Quattro robot

[Özgür10]

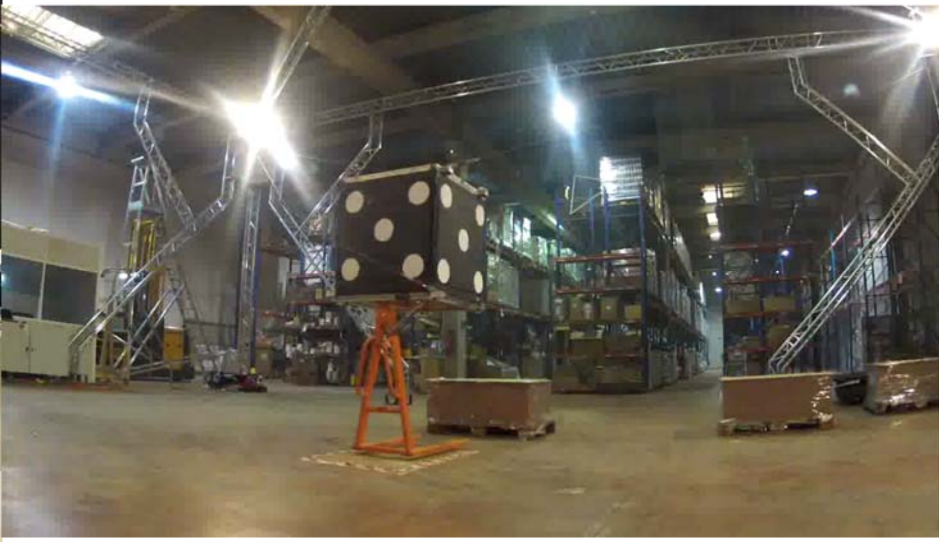


Vision Based Control of cable driven Parallel robot

[Dallej11, Dallej12]



Real Axe8
COGIRO project 2011

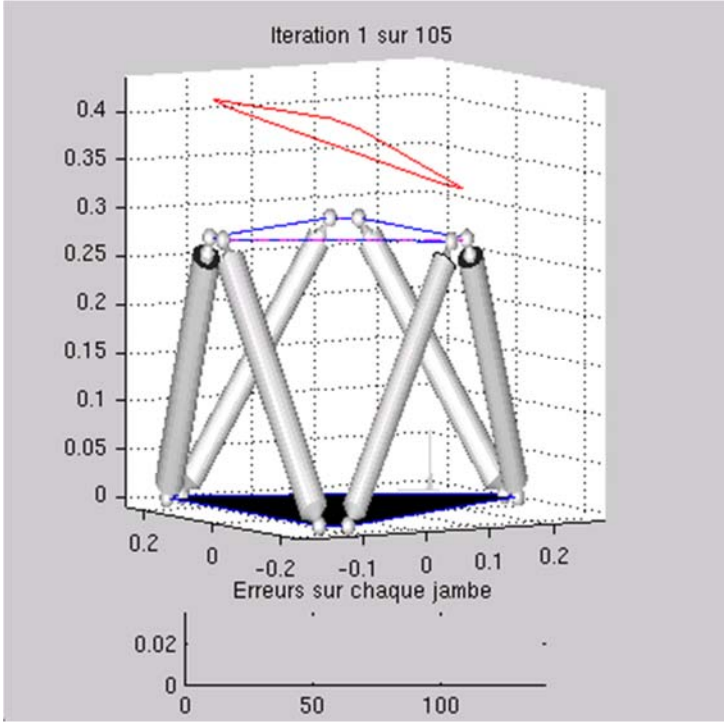


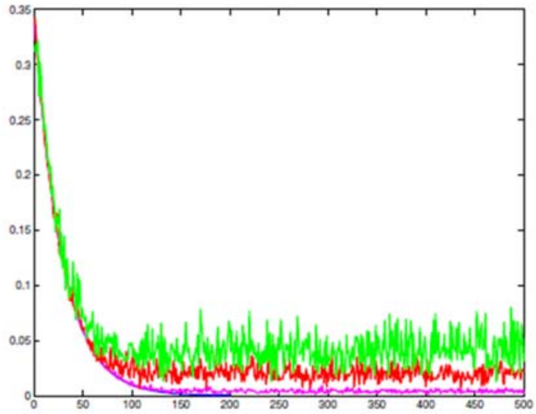
Large-Dimension Cable-Driven Parallel Robots
COGIRO project 2013

Some problems and questions in Kinematic Vision Based Control

Case of a Gough Stewart platform

[Andref05]



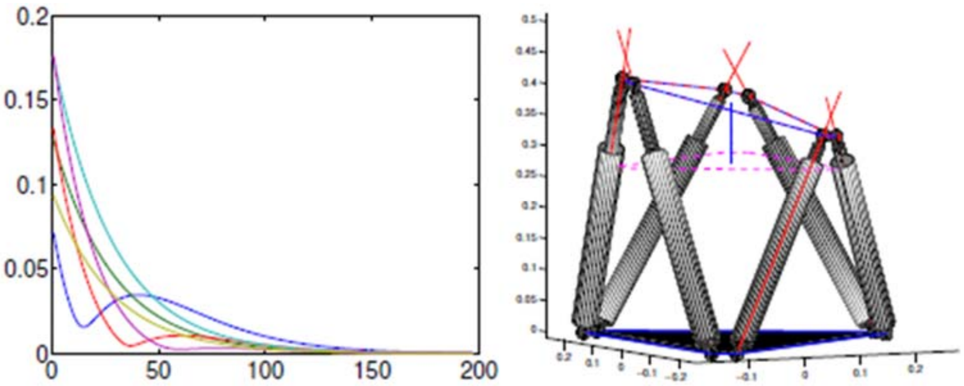


Robustness to noise : sum of squares of the errors $E^T E$ *vs* time with a noise amplitude of 0.01 deg (dashed), 0.05 deg (dashed) and 0.1 deg (dash-dotted).

Some problems and questions in Kinematic Vision Based Control

Case of a Gough Stewart platform

[Andref05]



Lucky convergence in the case where legs 2, 4 and 6 only are used for control

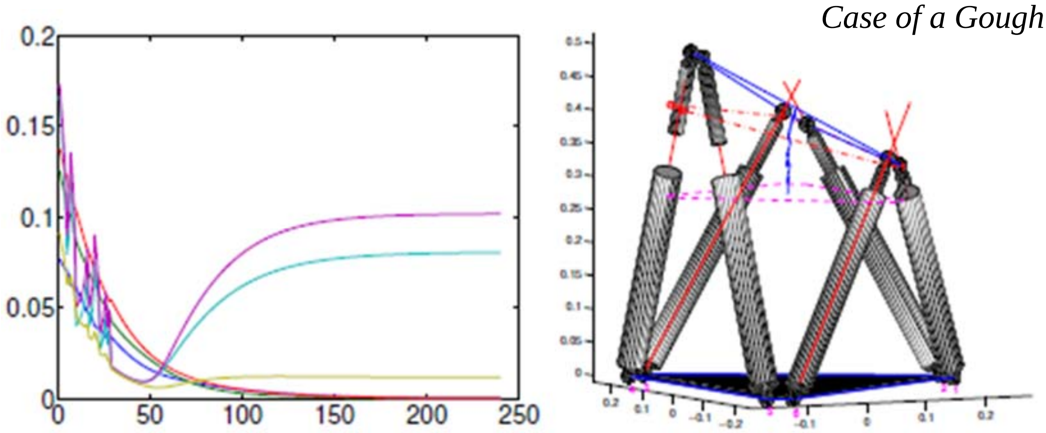
3 legs represent 3*2 d.o.f controlled

Does the 3 selected legs directions represent the state of the Robot?

Some problems and questions in Kinematic Vision Based Control

Case of a Gough Stewart platform

[Andref05]



Non-convergence in the case where legs 1, 2 and 3 only are used for control. The direction of the legs are superimposed (red) on the cylinders. A leg has converged to its desired orientation if its direction crosses the endeffector in the desired pose at the joint location. Notice that this happens only for the 3 controlled legs.

3 legs represents 3*2 d.o.f controlled. The 3 other legs converge to another equilibrium

How to choose the right set of 3 legs?

Why we are converging to another cartesian pose?

Some problems and questions in Kinematic Vision Based Control

What is the state of a parallel robot? Is it the legs space?

How to choose the right set of legs? (for control? for end effector pose estimation?)

Why we are converging to another cartesian pose?

Is it possible to better understand the mapping characteristics?

Part II The concept of Hidden Robot

– *Concept of Hidden Robot*
– *Controllability analysis*
– *Extension of the concept*
– *Conclusion*