Contributions to Visual Servoing for legged and linked multicomponent robots

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Outline

- Introduction
- Visual Servoing general ideas
- Visual Servoing for legged robots
- Control of Linked MCRS
- Conclusion

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Introduction

Motivation

- Vision has great importance in robotics since it allows to get a comprehensive description of the environment and is not an intrusive sensor.
- Visual Servoing systems define a direct relationship between vision and robot actuators.
- For legged robots we have found scarce literature on vision based control approaches.
- The Aibo robot is useful for research because it integrates a computer, vision system and articulators, being cheaper than the conventional robots for research.

Introduction

Motivation

- MCRS offer the possibility to execute a task through the cooperation of a set of robot that a single robot could not execute.
- Linked MCRS is a new category that has not been explored.
- Vision is the most suitable sensor for determining the form of the hose, no other sensors are available.

Introduction

Objectives

Develop applications of Visual Servoing to:

- Control of all the degrees of freedom of a legged robot.
- Control of Linked Multi-component Robots Systems.

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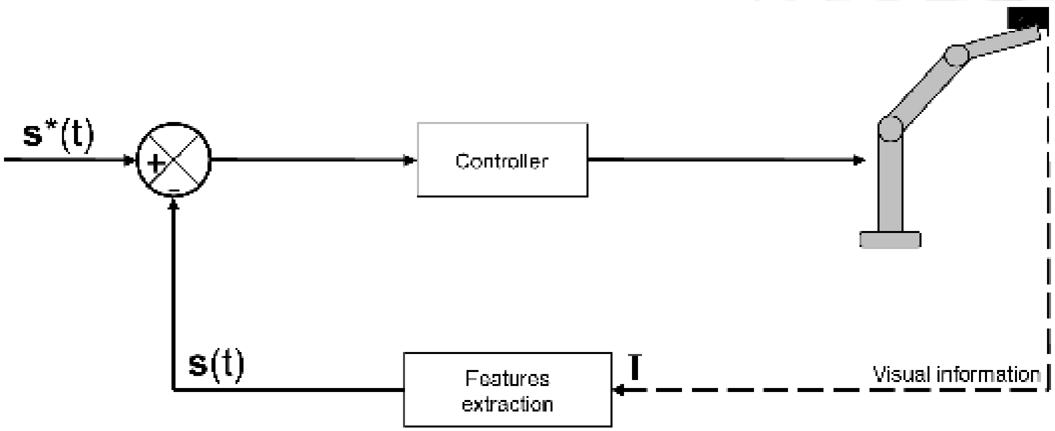
Visual Servoing General Ideas
Definition

The task of positioning one or more robots in order to get poses of their final effectors using as feedback the visual information extracted by one or more video-cameras.

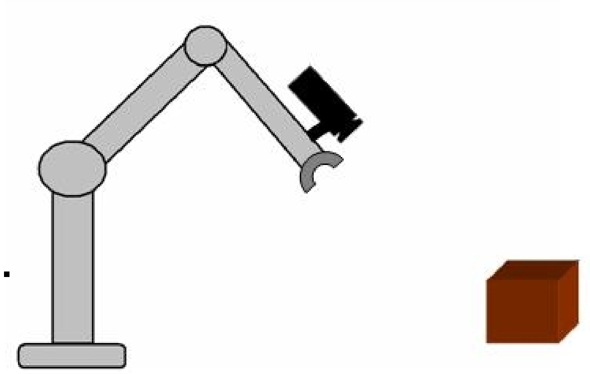
- For robotic manipulators: the pose of the final effector is relative to a target defined by a set of image features.
- For mobile robots: the pose is relative to some landmarks detected in the environment.

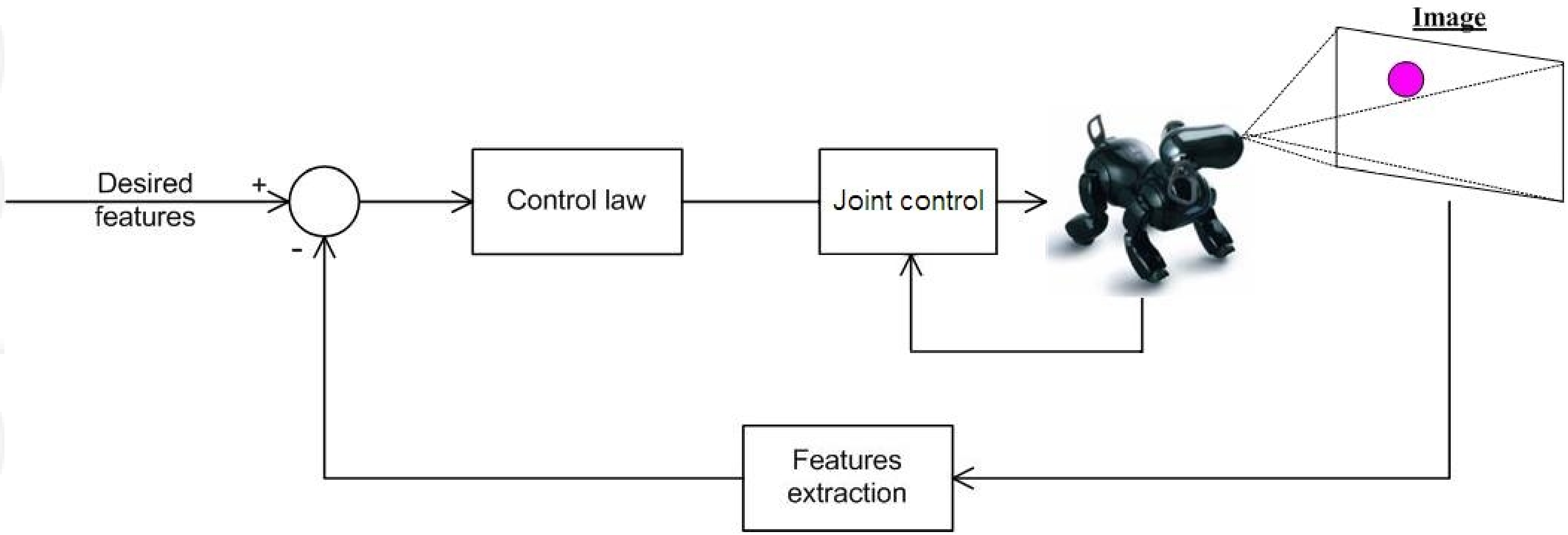


Classification according to camera configuration

Eye in hand

- Task is centered on the target object.
- Relation between posses of camera and robot's final effector is known and constant.
- Possibility of losing track of the target object.
- The camera intrinsic parameters may be required.



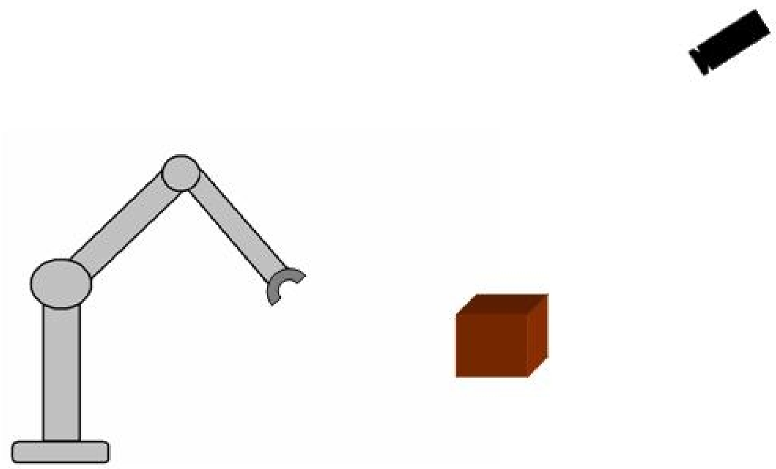


Visual Servoing General Ideas

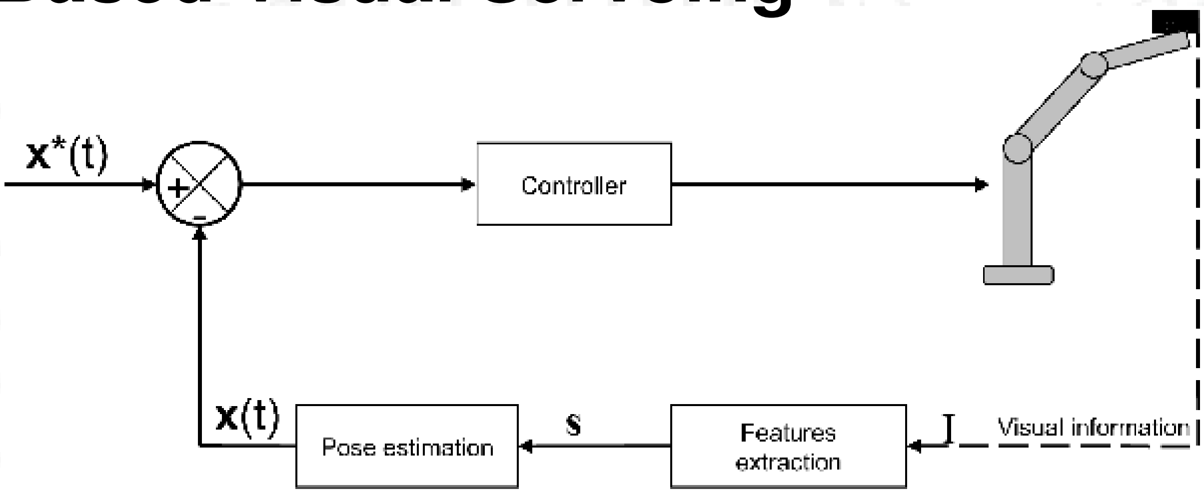
Classification according to camera configuration

Fixed camera

- Images of robots and the working space simultaneously.
- Fixed relationship between the camera reference system and the task reference system.
- Occlusions of the target object robots.
- It is necessary to calibrate the camera intrinsic and extrinsic parameters.



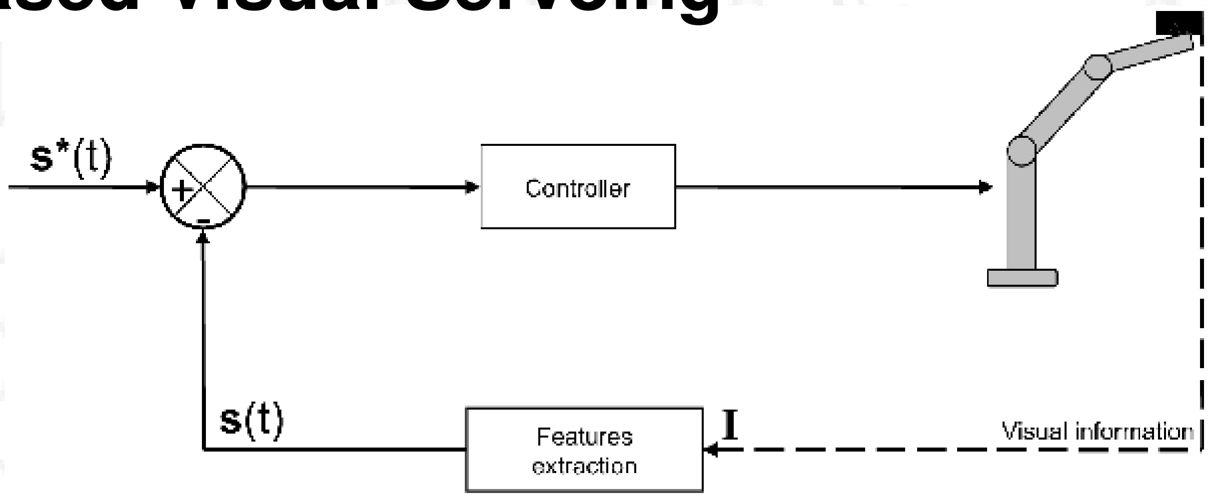
Position Based Visual Servoing



- The error signal is defined in the 3D space (the task space).
- Image features are extracted and used to estimate the pose through a tri-dimensional reconstruction of the environment's structure.

Visual Servoing General Ideas
Architectures

Image Based Visual Servoing



- The error signal is defined in the bi-dimensional image reference system.
- Image features are used directly to control the robot joints (Image Jacobian matrix).

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  - Coordinate reference systems
  - Basic problems
  - Direct Kinematics
  - Inverse Kinematics
  - Experiments
  - Conclusions
- Control of Linked MCRS
- Conclusion

Motivation

- Scarce Vision based control approaches for this kind of robots.
- Most of the approach only move the effectors linked directly to the camera or use high level control commands.

Objectives

- Build a detailed model of the image Jacobian matrix which formalizes a linear approach to the robot's kinematics.
- Taking into account all the effectors that can affect the image captured by the robot's camera.

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Visual Servoing for Legged robots

General description of the approach

- For solving the system we follow the conventional lines of the Image Based Visual Servoing (IBVS) systems.
- We build a locally linear kinematic model of the robot by composing the diverse Jacobians matrices that embody the dependencies among observation and control parameters.
- We propose a simple inversion of the model to obtain the desired control commands that will accomplish the minimization of the perceptual error detected in the vision system.

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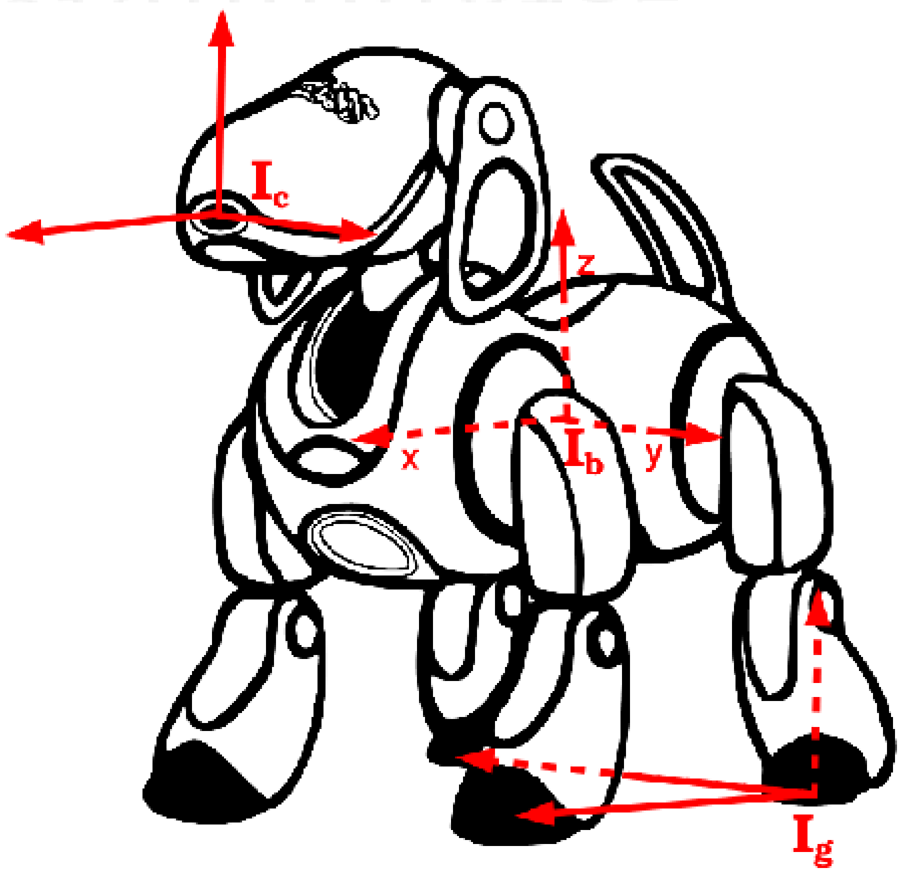
Visual Servoing for Legged robots

Coordinate reference systems



- Camera reference system
- Body reference system, whose origin is the geometrical center of the robot's body.
- Ground reference system, anchored to one of the basic ground support points defined later.

Outline

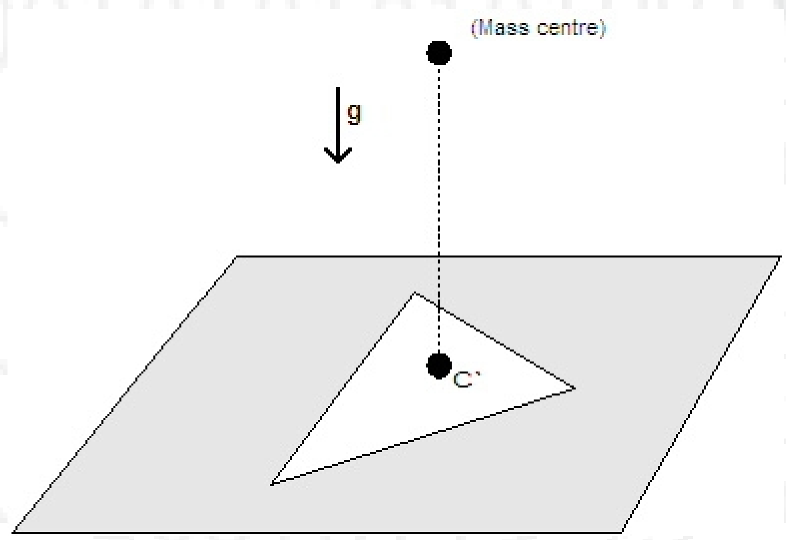
Basic problems

1) Determination of the ground plane.
2) Definition of a fixed ground reference system.

Basic problems

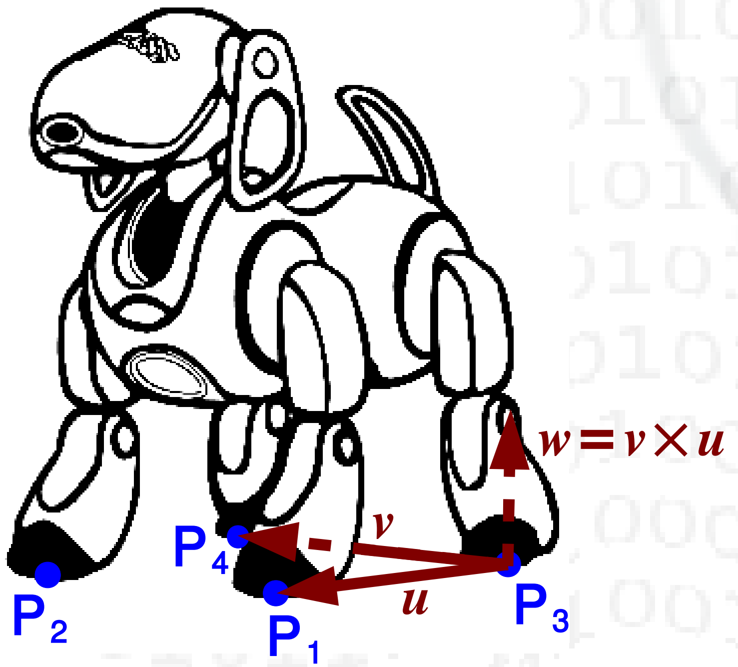
1. Determination of the ground plane.

We use a gravity sensor and the joint state information provided by the robot's basic control systems.



2. Definition of a fixed ground reference system.

We use the tips of the legs for defining the ground reference system.



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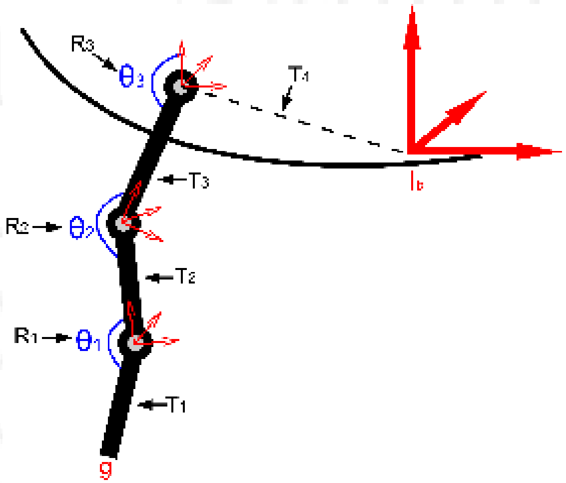
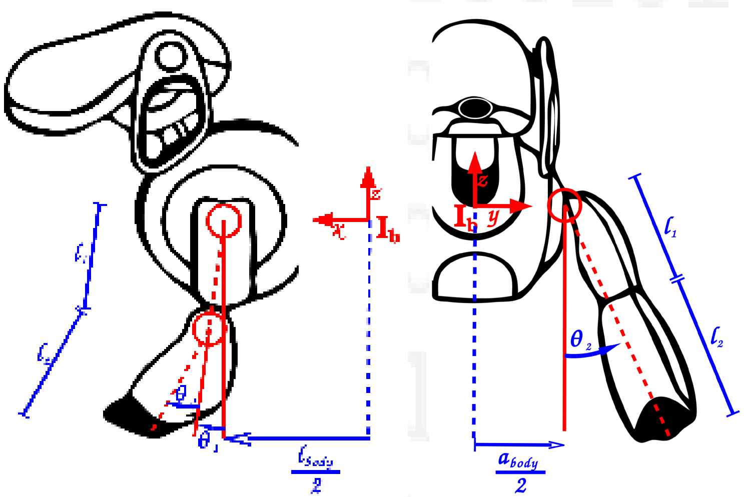
Direct Kinematics

Legs' degrees of freedom



$$\begin{pmatrix} g \\ 1 \end{pmatrix} = T_{n+1} \ldots R_n \cdot T_n \ldots R_1 \cdot T_1 \begin{pmatrix} \mathbf{0} \\ 1 \end{pmatrix}$$



$$\begin{pmatrix} x_p \\ y_p \\ z_p \\ 1 \end{pmatrix} = T_a \cdot T_b \cdot R_1 \cdot R_2 \cdot T_1 \cdot R_3 \cdot T_2 \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

Support points

The **basic support points** are the tips of the three legs that determine the supporting plane where it is standing on.

$$G_\pi = \left(g_1, \quad g_2, \quad g_3 \right)^t$$

The **extended support points** are the tips of the robot's legs that are in contact with the ground

$$G_e = \{ g \quad s.t. \, | a\, g_x + b\, g_y + c\, g_z | < tol \}$$

Vectors of parameters

- We define the vectors of parameters as the composition of the upper articulations joint angles and the support points.

Basic parameter vector

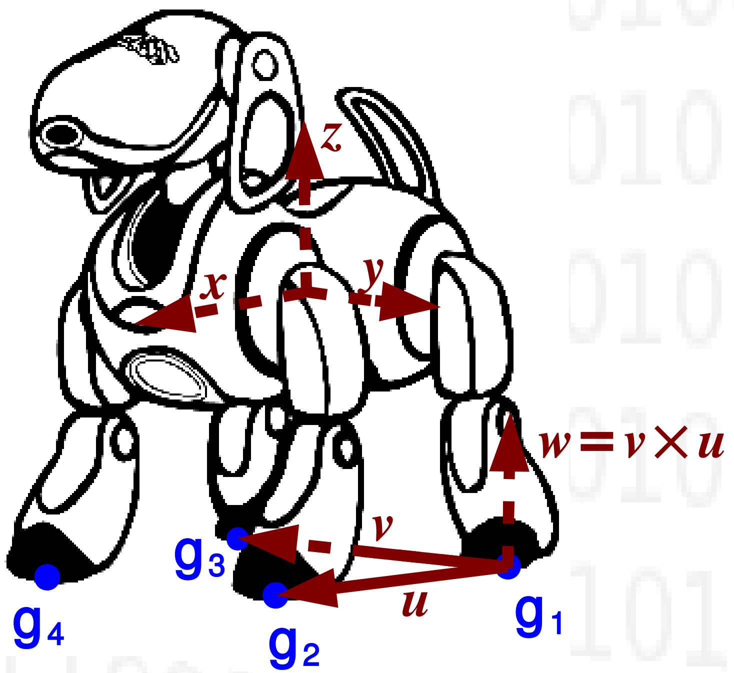
$$\boldsymbol{p}_{\boldsymbol{\pi}} = \begin{pmatrix} \boldsymbol{\theta}_u \\ \boldsymbol{G}_\pi \end{pmatrix}$$

Extended parameter vector

$$\boldsymbol{p} = \begin{pmatrix} \boldsymbol{\theta}_u \\ \boldsymbol{G}_e \end{pmatrix}$$

Transformation between ground and body systems

Legs degrees of freedom



$$R_0 = \begin{pmatrix} u & v & v \times u \\ 0 & 0 & 1 \end{pmatrix}$$

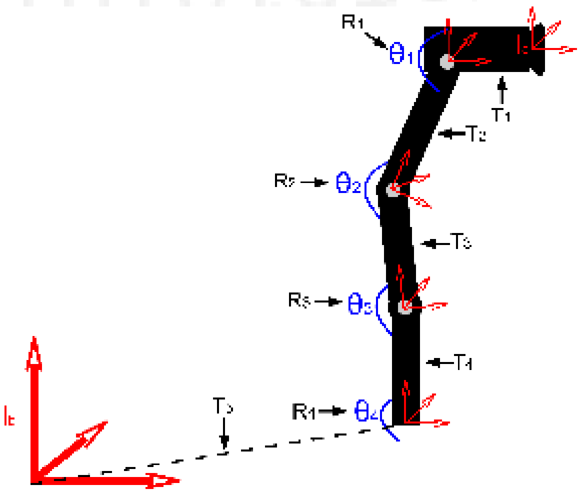
$$T_0 = \begin{pmatrix} I_{3\times 3} & \boldsymbol{g}_1 \\ \boldsymbol{0} & 1 \end{pmatrix}$$

$${}_b I_g = T_0 \cdot R_0$$

Visual Servoing for Legged robots

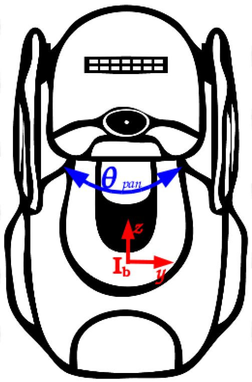
Direct Kinematics

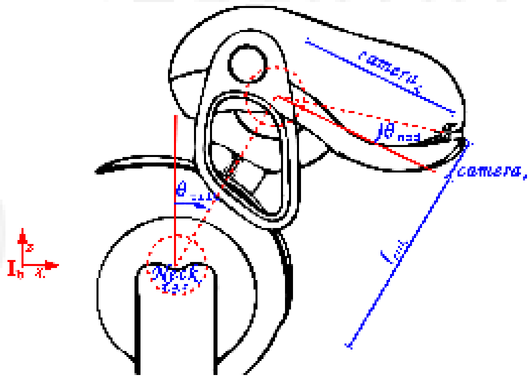
Transformation between body and camera systems



Upper body degrees of freedom

$$ {}_{b}I_{c} = \left(T_{m+1} \cdot R_{m} \cdot T_{m} \ldots R_{1} \cdot T_{1} \right) $$



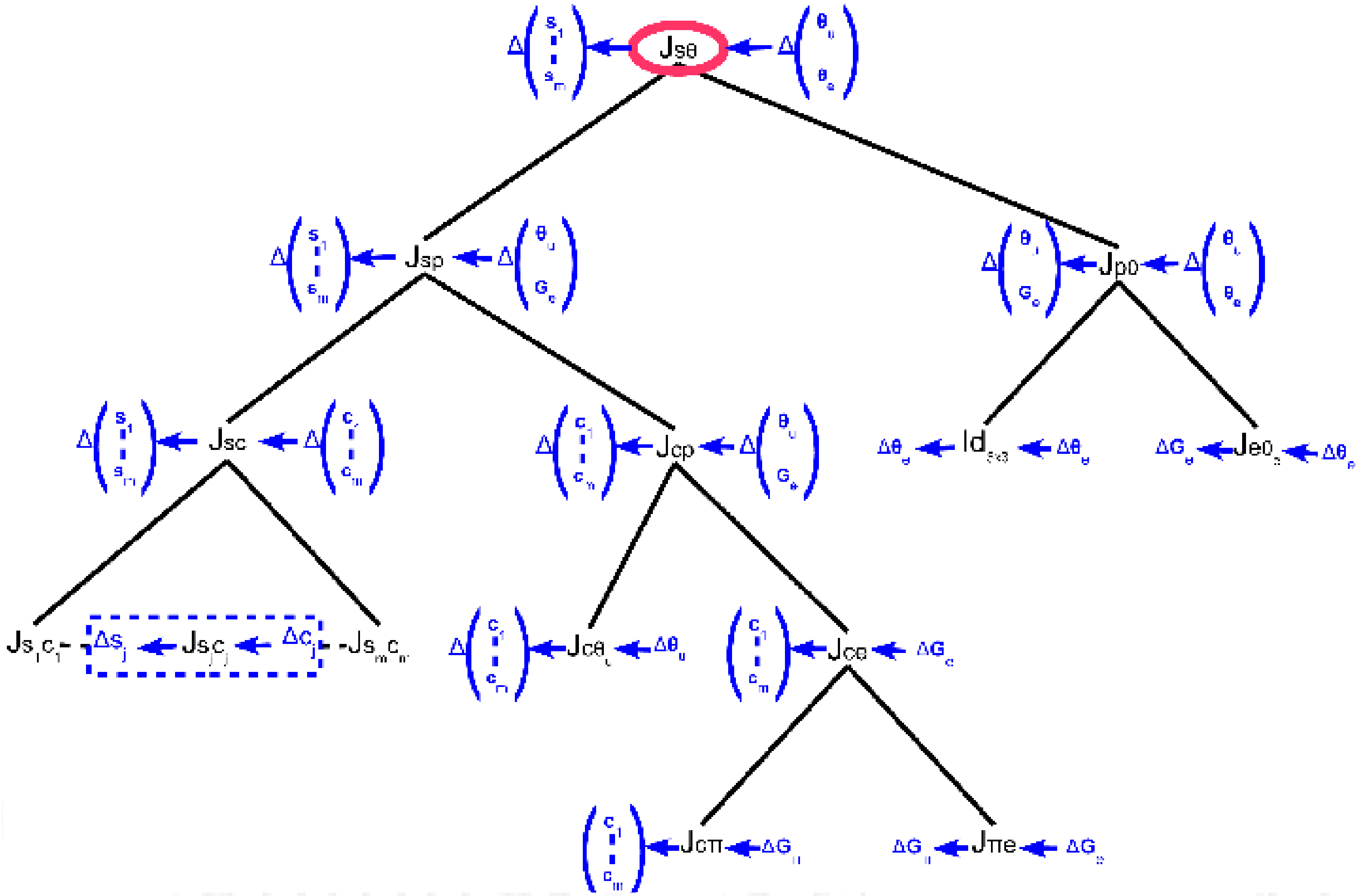


$$ {}_{b}I_{c} = \left(T_{3} \cdot R_{2} \cdot T_{2} \cdot R_{1} \cdot T_{1} \right) $$

Visual Servoing for Legged robots

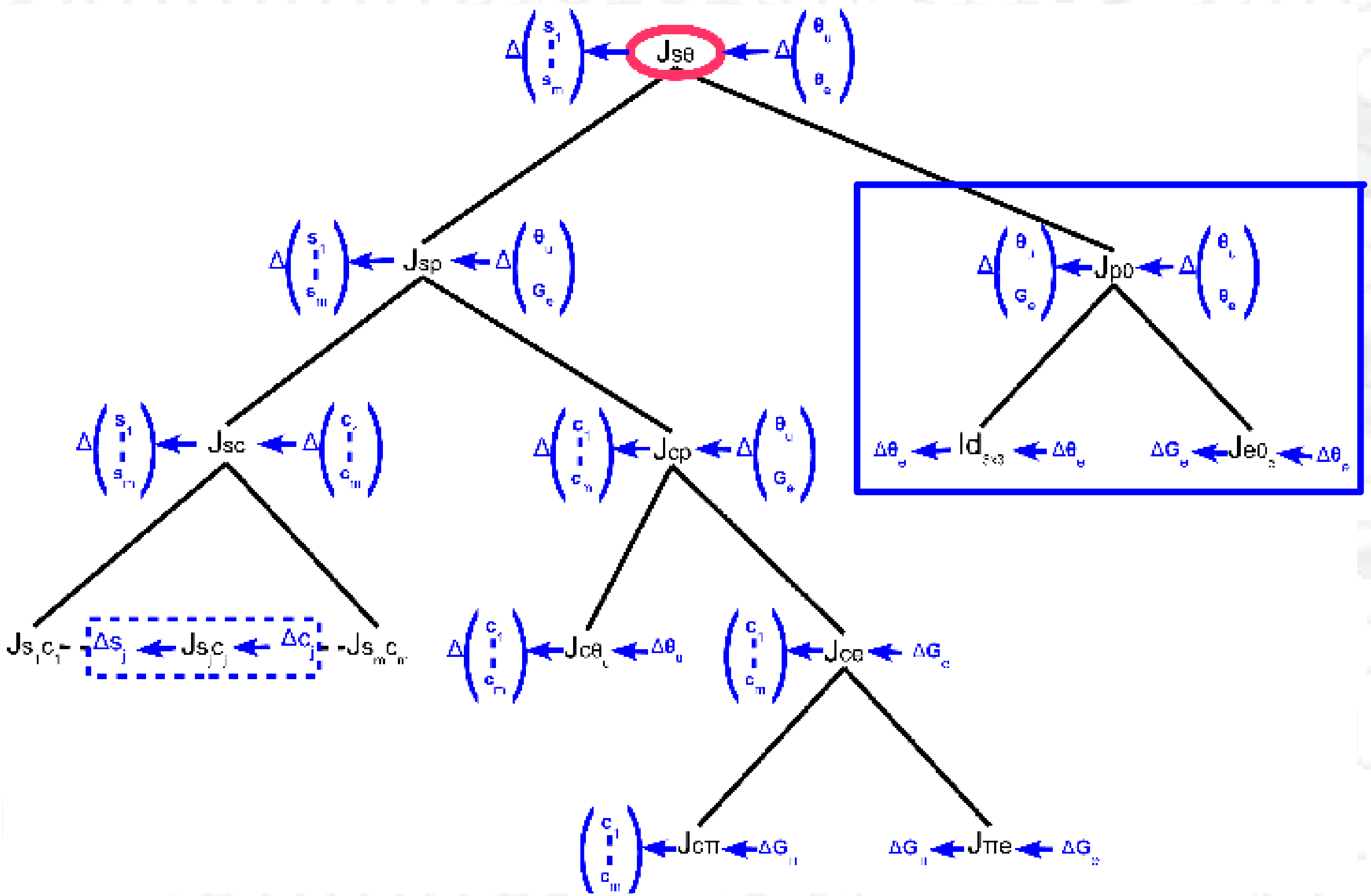
Direct Kinematics

Structure of direct kinematic function



Direct Kinematics

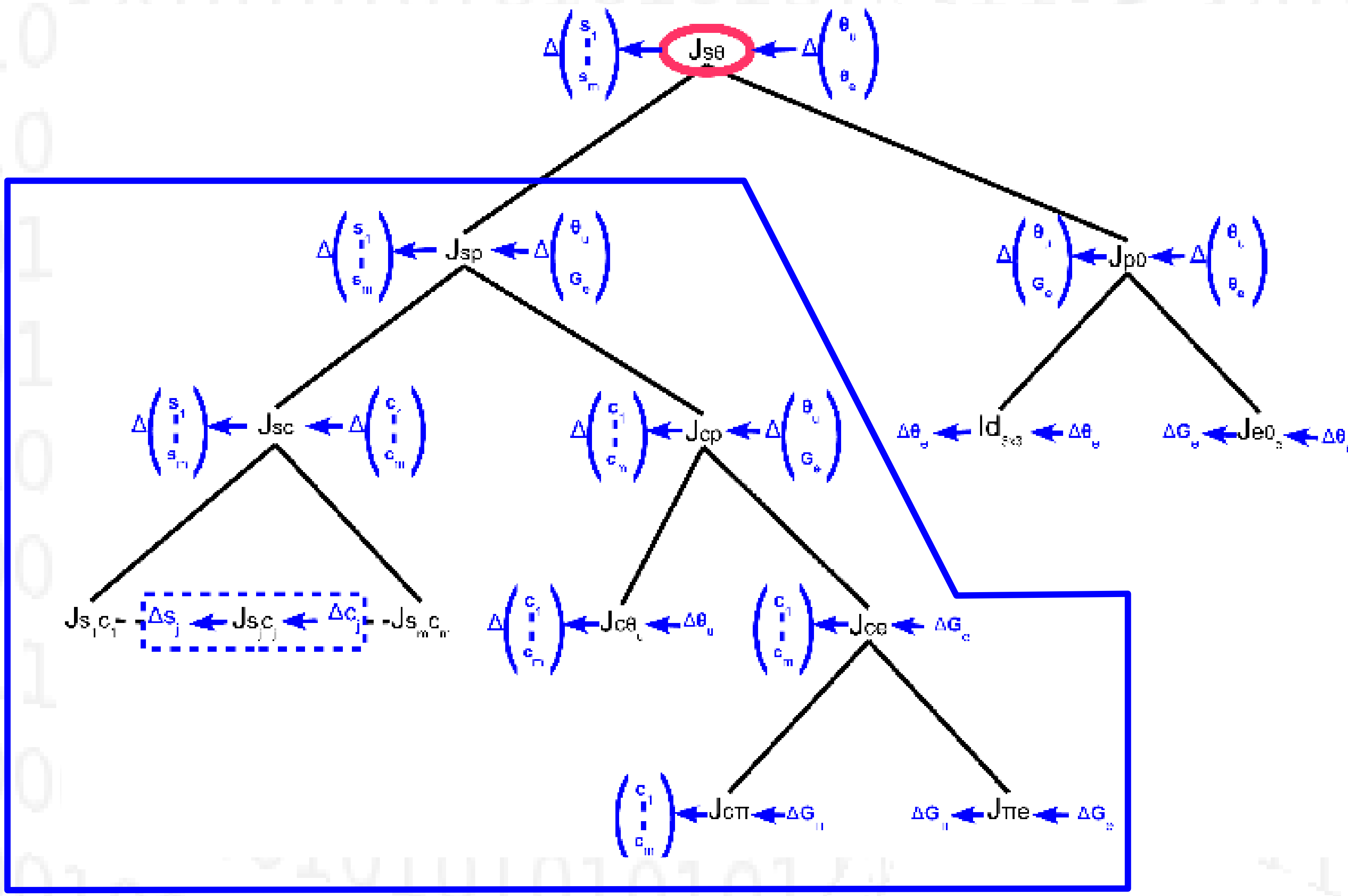
Structure of direct kinematic function



Visual Servoing for Legged robots

Direct Kinematics

Structure of direct kinematic function



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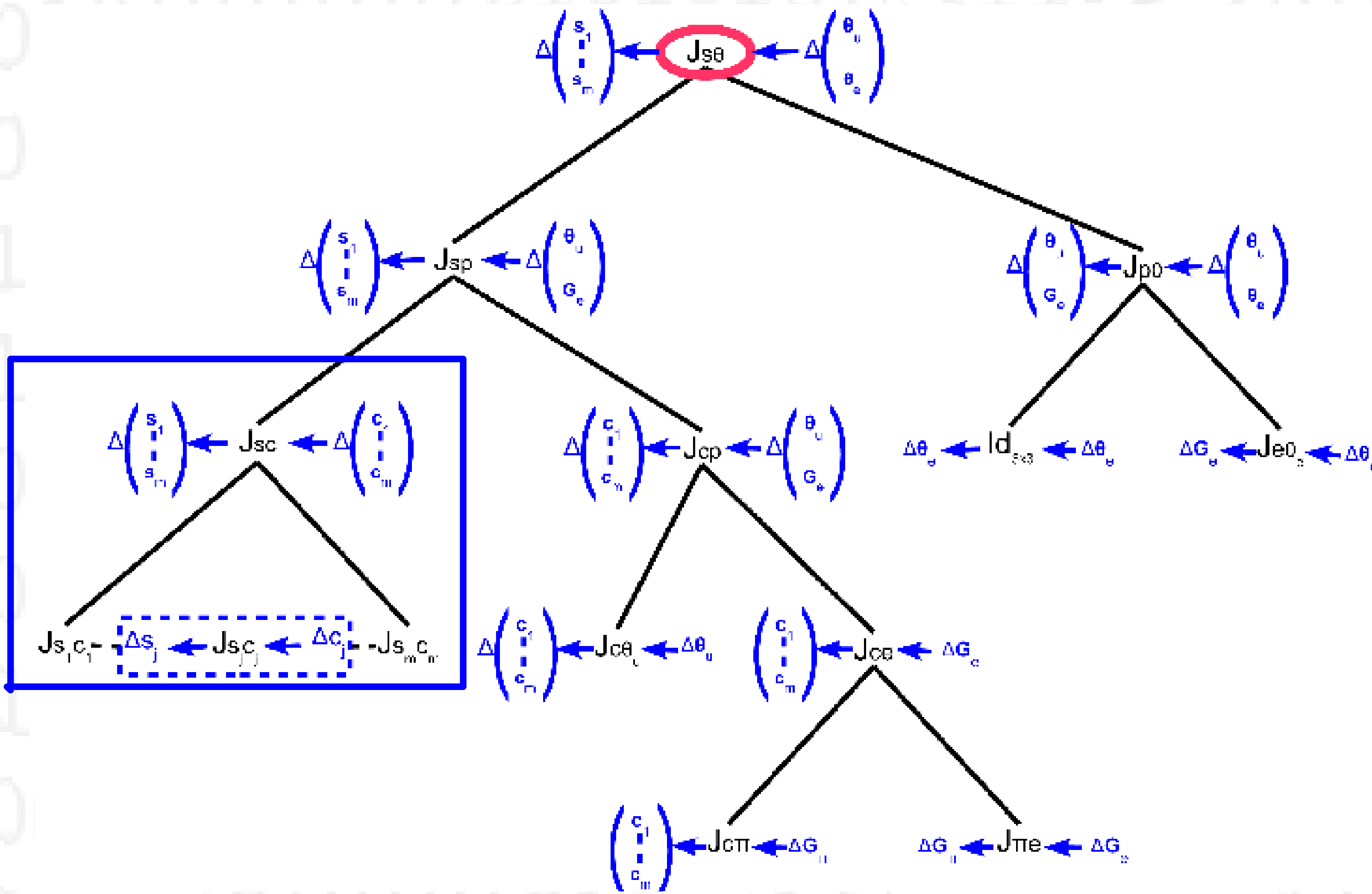
Structure of direct kinematic function



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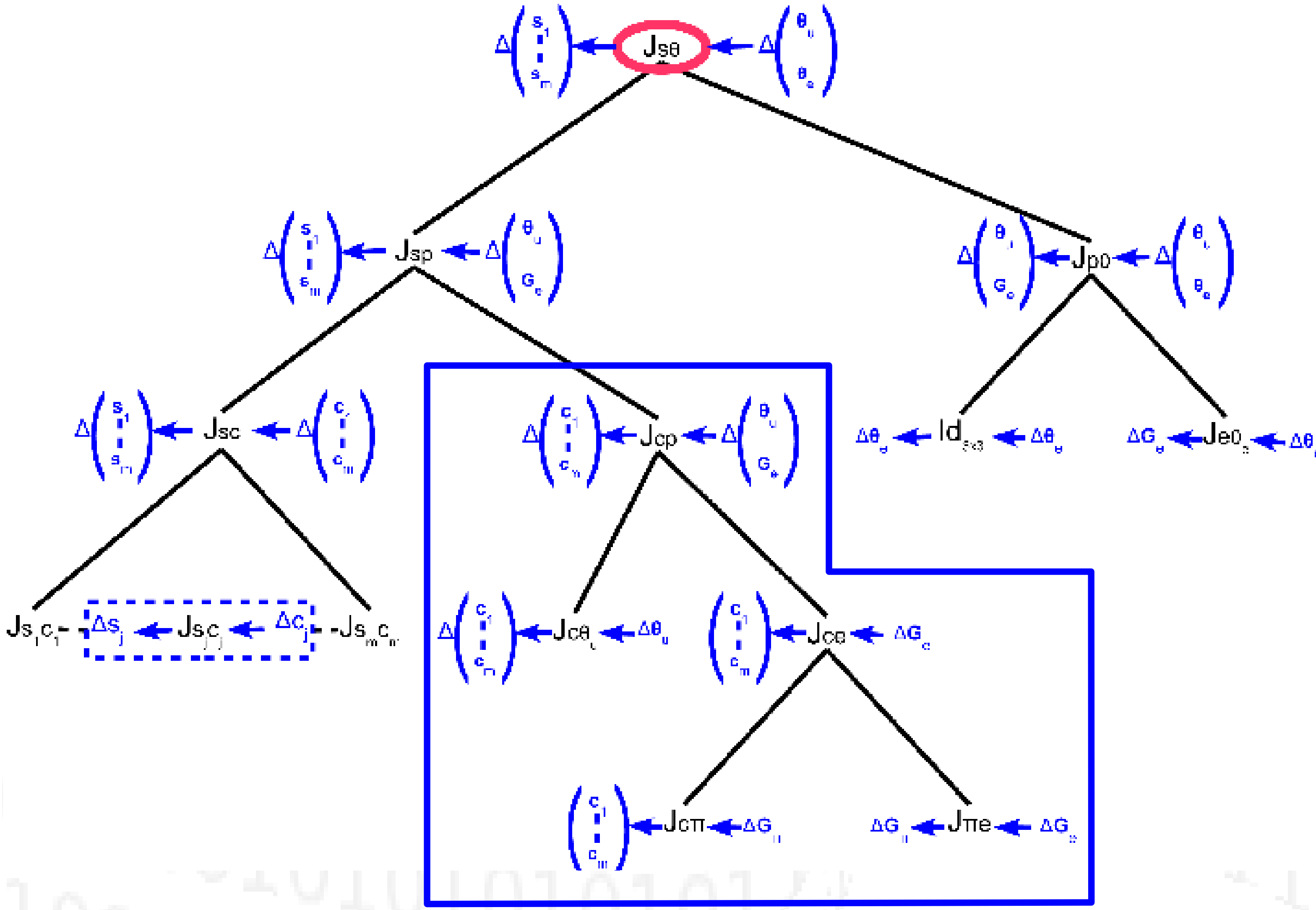
Direct Kinematics

Structure of direct kinematic function



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Inverse Kinematics

Objective: obtain the joints velocities in order to minimize the norm of the visual error:

$$\min_{\dot{\theta}} \| \boldsymbol{s}^{*} - (s + \boldsymbol{J}_{s\theta} \dot{\boldsymbol{\theta}}) \|$$

Restriction: keep the support points fixed on the ground

We try to maintain the distances between support points constant

Keeping the supporting points fixed on the ground

Distance between support points

$$\boldsymbol{d}=\begin{pmatrix} d_1 \\ \vdots \\ d_{n(n-1)} \end{pmatrix}$$

Jacobian of ***d***

$$J_{de}=\begin{pmatrix} \frac{\partial d_1}{\partial \boldsymbol{e}_1} & \cdots & \frac{\partial d_1}{\partial \boldsymbol{e}_n} \\ \vdots & \vdots & \vdots \\ \frac{\partial d_n}{\partial \boldsymbol{e}_1} & \cdots & \frac{\partial d_n}{\partial \boldsymbol{e}_n} \end{pmatrix}$$

Extending the sensitivity to upper joints

$$J_{dp}=\begin{pmatrix} o_{n\times m} & 0 \\ 0 & J_{de} \end{pmatrix}$$

$$\Delta \boldsymbol{d} \approx J_{dp}\begin{pmatrix} \Delta \boldsymbol{\theta}_u \\ \Delta \boldsymbol{G}_e \end{pmatrix}$$

Visual Servoing for Legged robots

Inverse Kinematics

Control of image features

$$\Delta \boldsymbol{p}^1 = [(I - J_{dp}^{+} J_{dp})(J_{sp}^{+})] k_s \Delta \boldsymbol{s}$$

Control of distances between support points

$$\Delta \boldsymbol{p}^2 = [(I - J_{sp}^{+} J_{sp})(J_{dp}^{+})] k_d \Delta \boldsymbol{d}$$

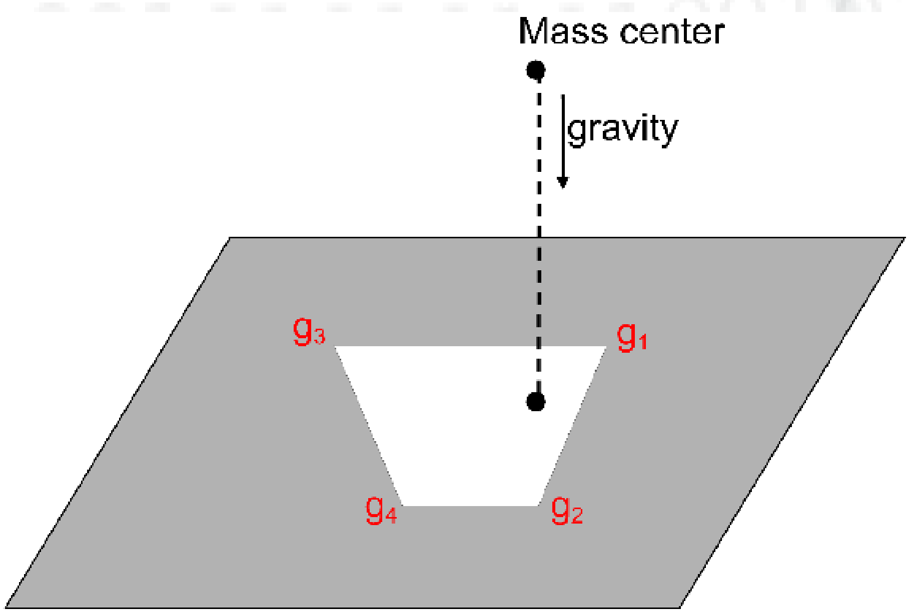
Global control

$$\Delta \boldsymbol{\theta} = J_{p\theta}^{+} \{\Delta \boldsymbol{p}^1 + \Delta \boldsymbol{p}^2\}$$

Visual Servoing for Legged robots

Inverse Kinematics

- The blind application of this control strategy may lead the robot to unstable configurations for a standing pose.
- When stability is compromised we restrict the Visual Servoing to the upper degrees of freedom.



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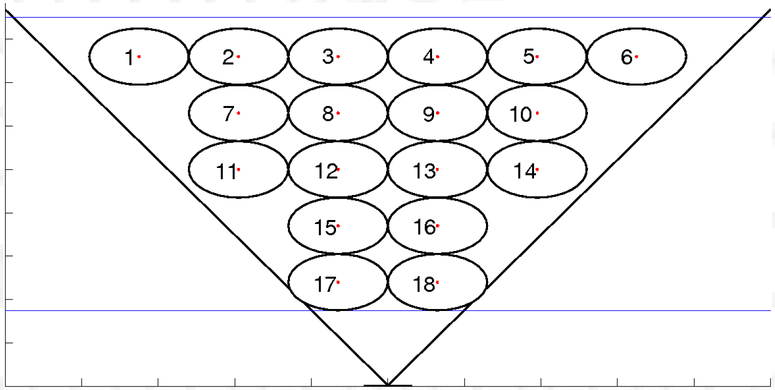
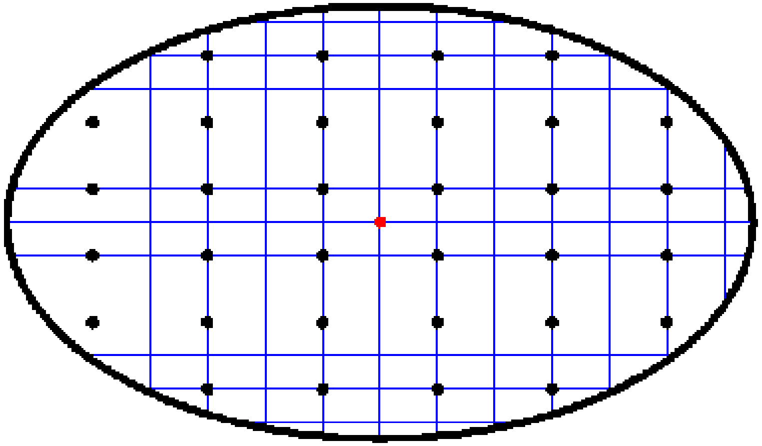
Experimentation with an Aibo ERS7 robot

Experiments under controlled conditions



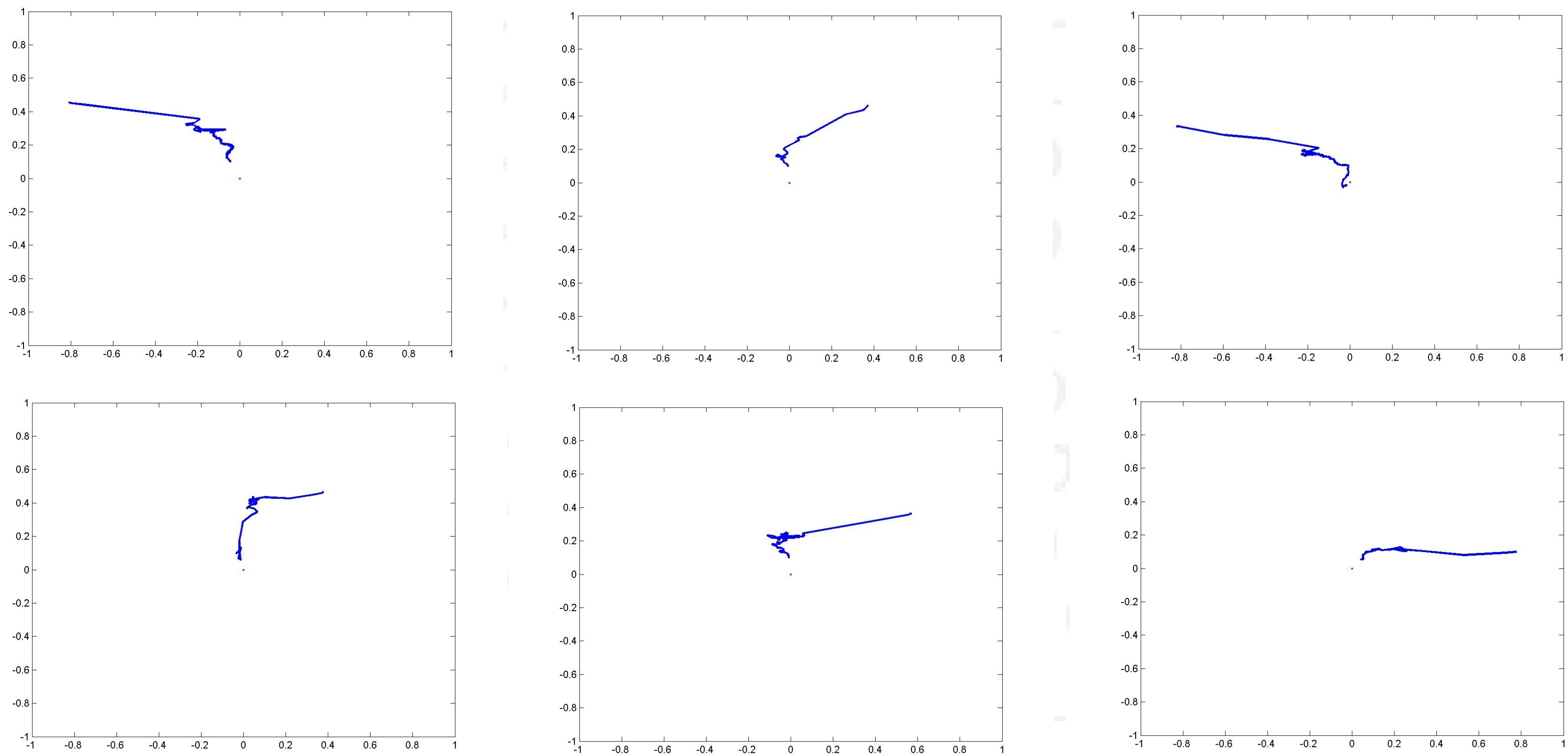


Experiments under controlled conditions

Video

Empirical results

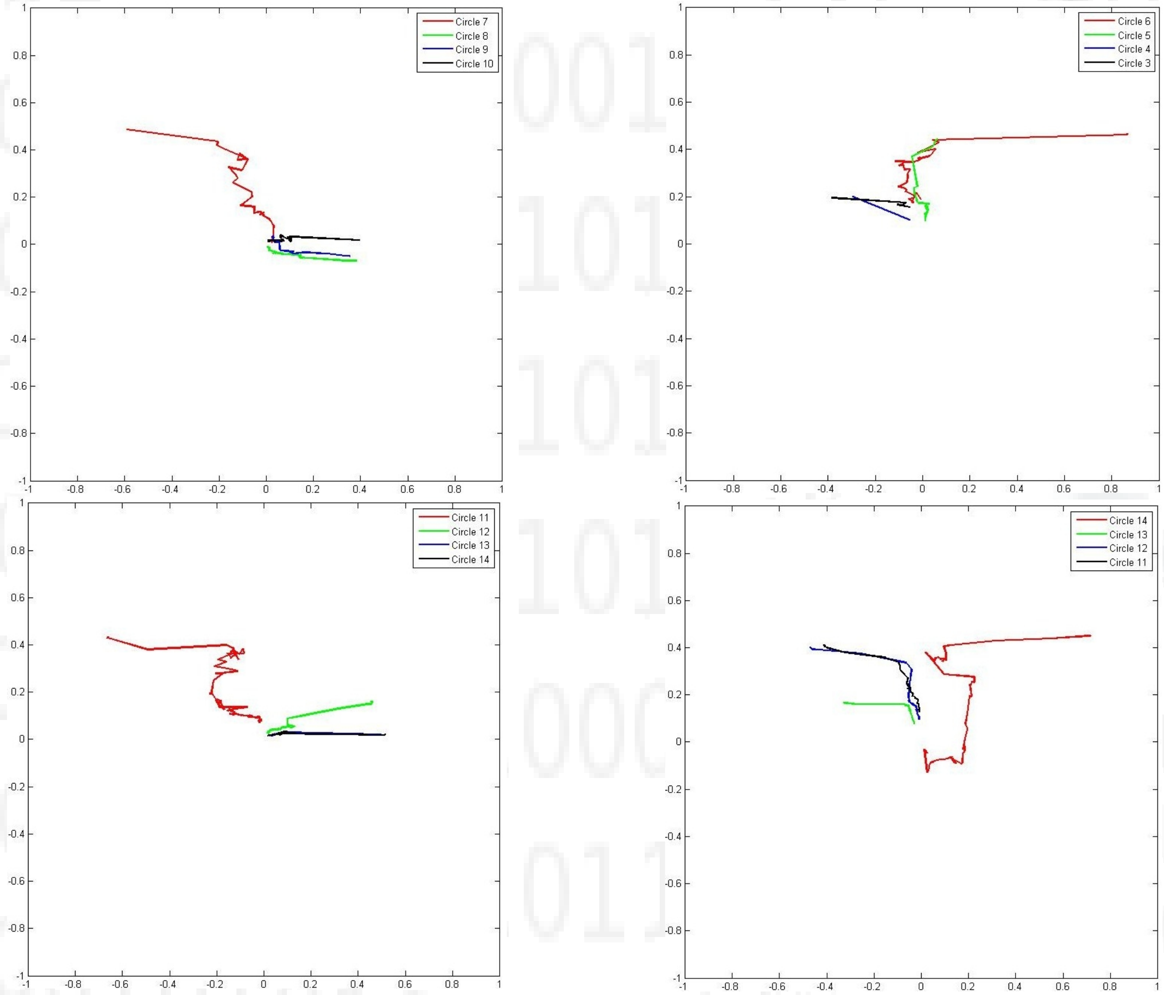
Sample trajectories of the ball center in the image with the ball placed in some position inside the uncertainty circles.



Experimentation with an Aibo ERS7 robot

Empirical results

Sample trajectories for a moving ball

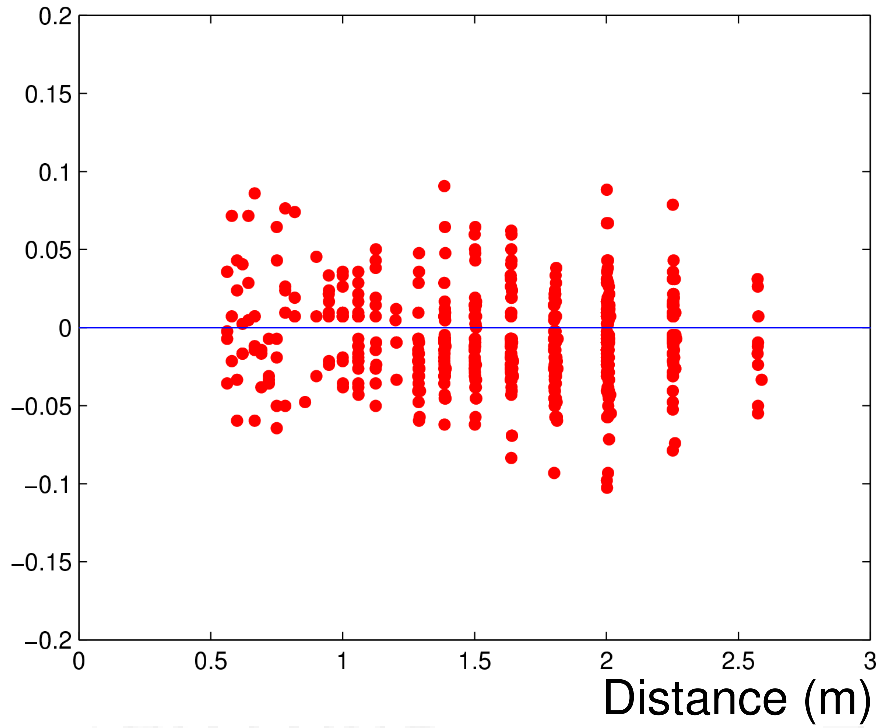


Experimentation with an Aibo ERS7 robot

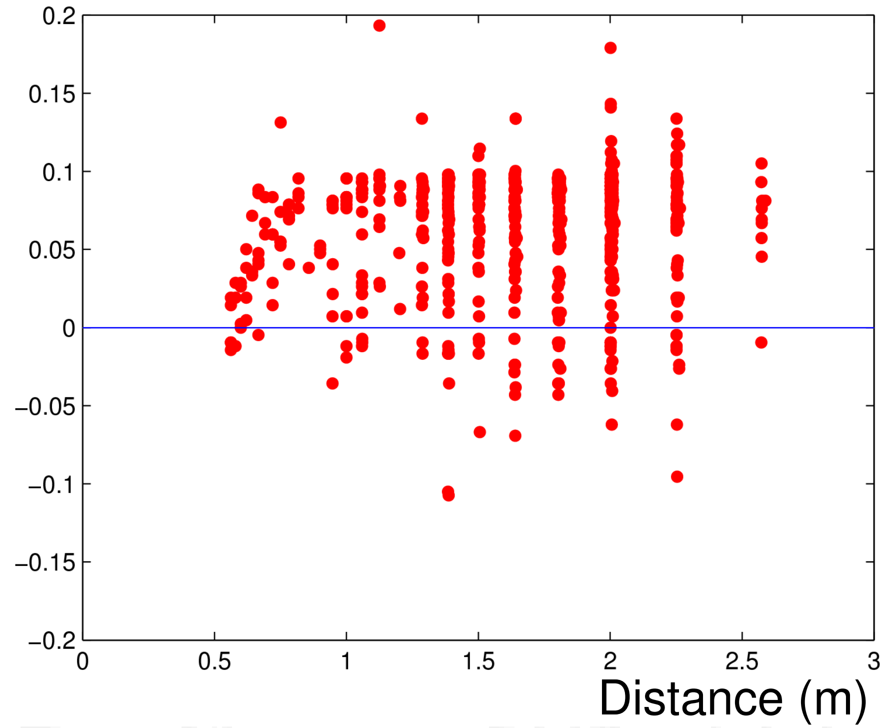
Empirical results

Final error distribution versus 3D distance to the ball

Error in the horizontal axis



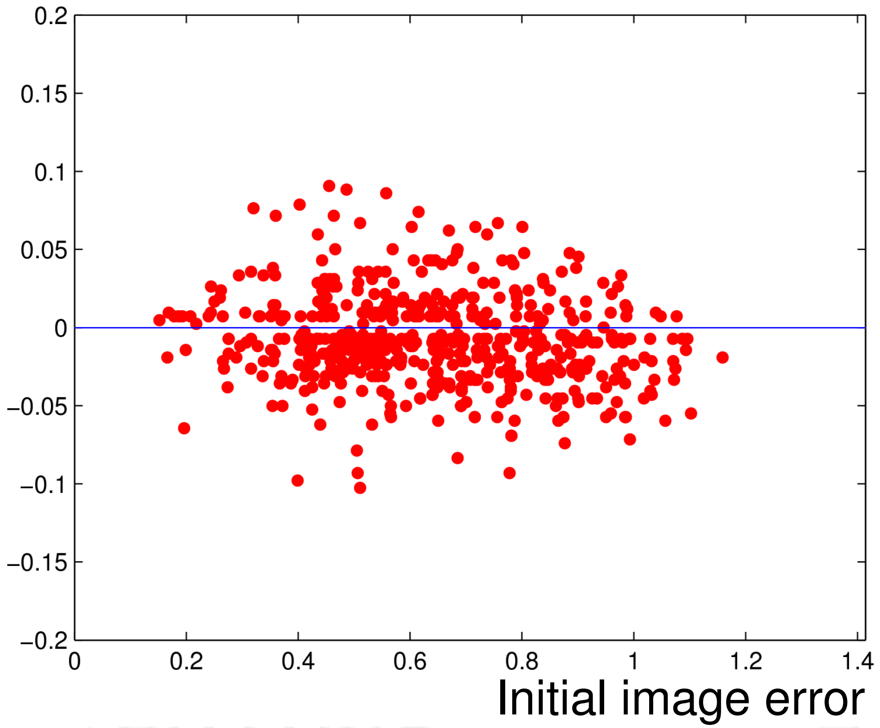
Error in the vertical axis



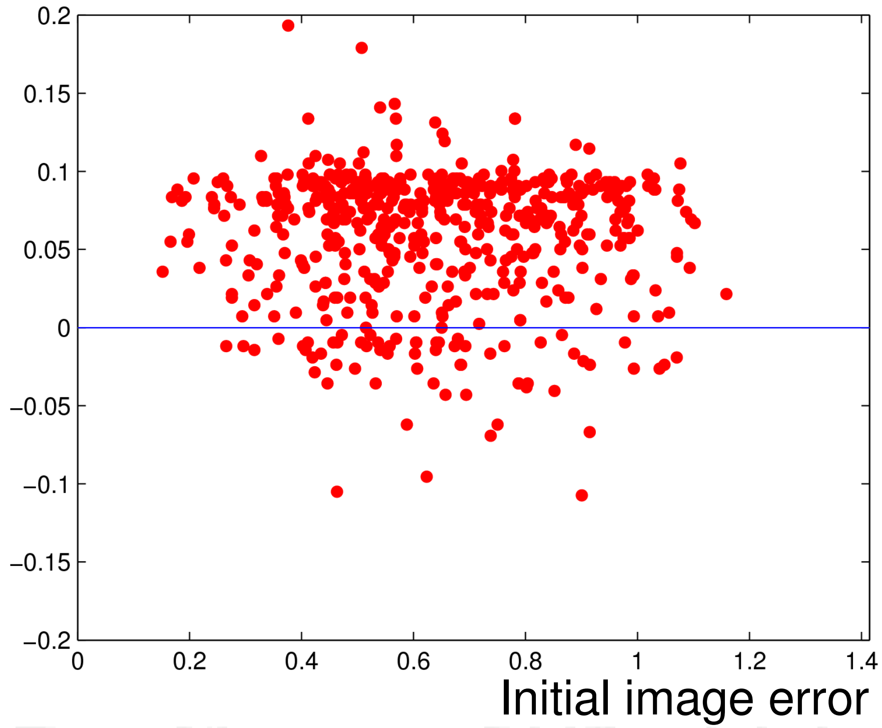
Empirical results

Final error distribution versus initial distance in image plane

Error in the horizontal axis



Error in the vertical axis



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Visual Servoing for Legged robots

Conclusions

- We have developed a Visual Servoing approach for all the degrees of freedom of a legged robot.
- We have constructed the full Jacobian matrix that linearizes the functional dependence of visual observations by the robot camera on the robot degrees of freedom.

Visual Servoing for legged robots

Conclusions

- We have developed a physical realization on the Aibo ERS7 robot.
- The approach obtains the desired control commands.
- The approach performs in real time in the on-board processor of the robot.
- The approach is highly robust to positioning of the ball in the field of view of the robot.
- Very low final error, whose distribution is invariant to the distance of the ball to the camera.

Visual Servoing for Legged robots

Conclusions

As the main sources of convergence problems we have identified the following ones:

- The linear nature of the approach.
- The resolution and power of the physical servo-motors.
- The problems in the image segmentation.

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  - Linking element model
  - Linked MCRS configuration
  - Linked MCRS control
  - Linked MCRS heuristics
  - Simulation
  - Real life experimentation
  - Conclusions
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Control of Linked MCRS
Motivation

- When a task can not be performed by a single robot, a team of robots may cooperate with each other in order to execute it.

- Categorization of MCRS based on morphological features by Duro et al.:
  - Modular: rigid connections between robots.
  - Distributed: there is no physical union.
  - Linked: the robots are linked by a passive element.

- Linked MCRS is a new category that has not been explored.

Control of Linked MCRS

Objectives

- Obtain a formal model of the Linked MCRS, for the transport of a hose, from a geometrical and dynamical point of view.
- The model could be easily adapted to new instances of the system, varying the parameters of the linking element and/or the individual robots.
- This model would be used to:
  - Simulate the system.
  - Test heuristics and control strategies.
- Derive control strategies from the analytical model.
- Demonstrate empirically the fundamental differences between Distributed and Linked MCRS.

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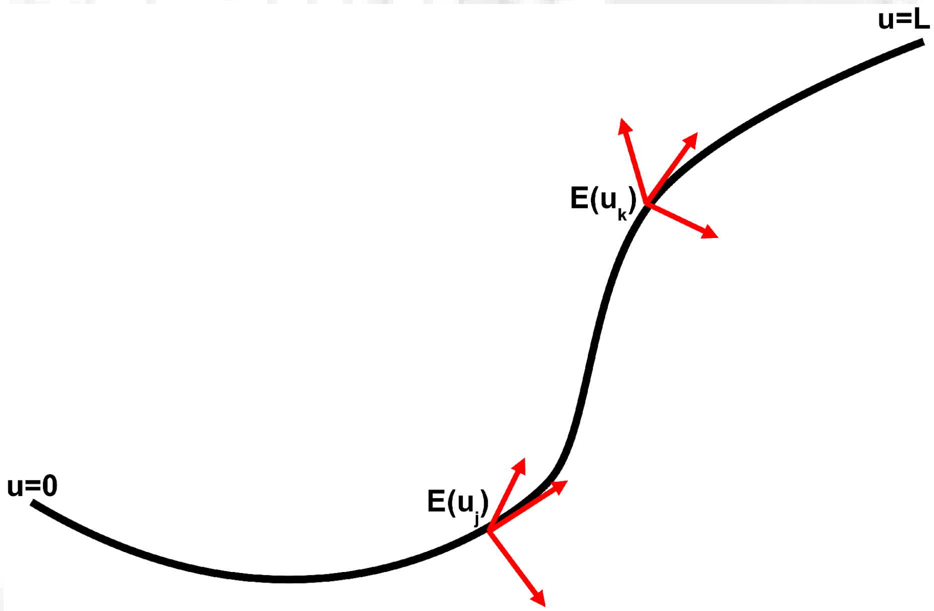
Linking element model

Cosserat rod theory

$$E(u)=[e_1, e_2, e_3, r](u)$$

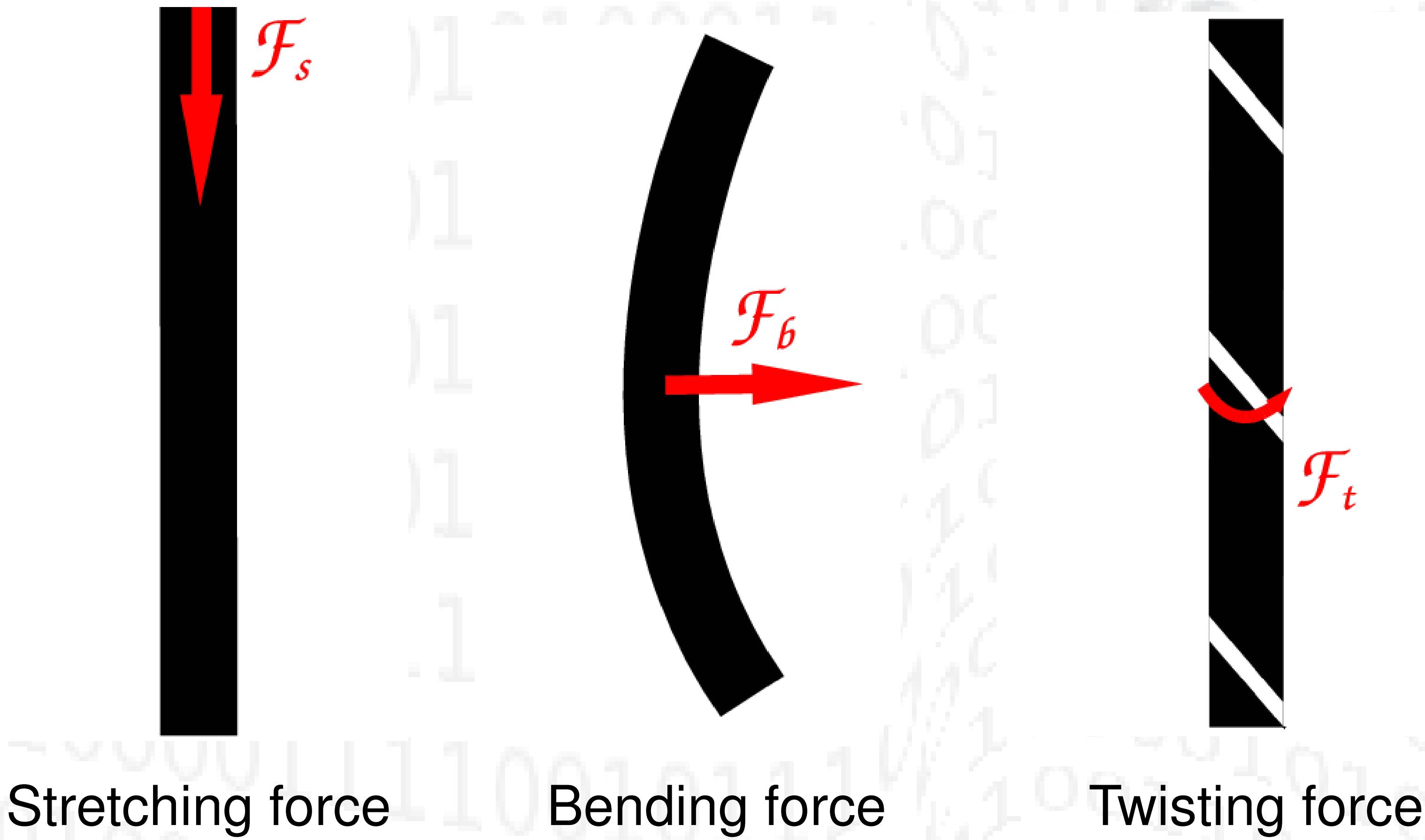
An uni-dimensional object is described by a curve $r(u)$ and a coordinate frame of director vectors $[e_1, e_2, e_3](u)$ attached to each point of the curve.

$$u \in [0, L]$$



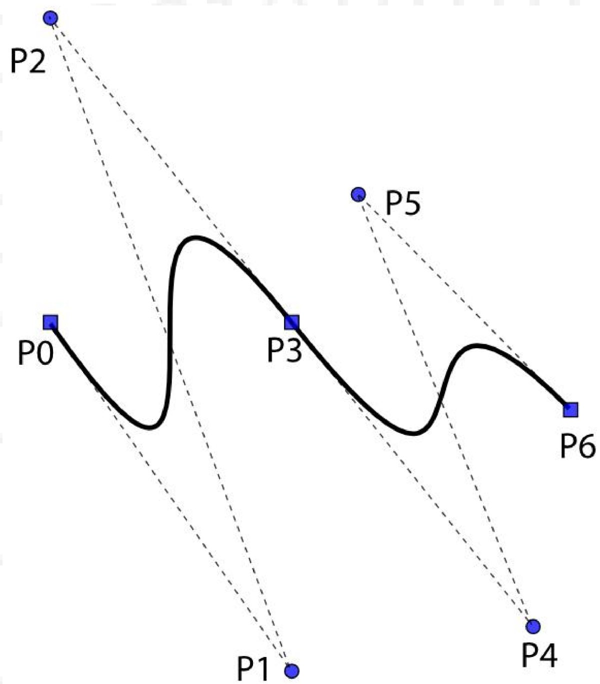
Linking element model

Forces induced by the potential energy of the hose



Linking element model

Dynamic splines

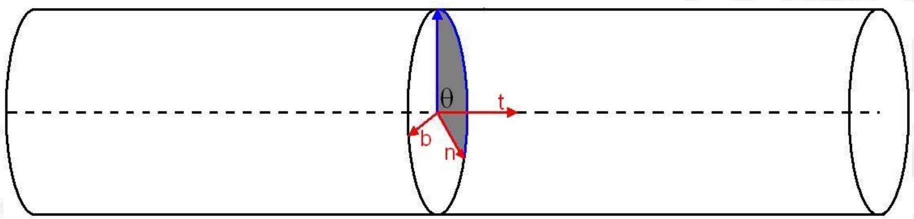


$$q(u,t)=\sum_{i=0}^{n} N_i(u)\cdot p_i(t)$$

Problems with splines model: Are based on the control points of the spline, therefore they are not suitable for representing the hose torsion.

Geometrically Exact Dynamic Splines (INRIA 2006)

GEDS takes into account the torsion by using a fourth component in the control points.



$$\boldsymbol{p}_i = \left(x_i, \quad y_i, \quad z_i, \quad \theta_i \right)$$

Linking element model

Energy formulation

Potential energy

$$U = \frac{1}{2} \cdot \int_0^L \epsilon^t H \epsilon \, du$$

$$H = \begin{vmatrix} E_s & 0 & 0 \\ 0 & E_t & 0 \\ 0 & 0 & E_b \end{vmatrix}$$

ϵ_s Stretching deformation

ϵ_t Twisting deformation

ϵ_b Bending deformation

Kinetic energy

$$T = \frac{1}{2} \cdot \int_0^L \frac{d\boldsymbol{q}^t}{dt} J \frac{d\boldsymbol{q}}{dt} du$$

$$J = \begin{vmatrix} \mu & 0 & 0 & 0 \\ 0 & \mu & 0 & 0 \\ 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & I \end{vmatrix}$$

μ Linear density

I Polar momentum of inertia

Dynamics

We want to obtain the forces that robot must apply to obtain in order to approximate the desired acceleration of the hose

Lagrange equation

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\boldsymbol{p}}_i}\right) = \boldsymbol{F}_i - \frac{\partial U}{\partial \boldsymbol{p}_i}$$

Defines a mathematical relation between:

- U, potential energy.
- T, kinetic energy.
- F, external forces.

$$M\,\boldsymbol{A} = \boldsymbol{F} + \boldsymbol{P}$$

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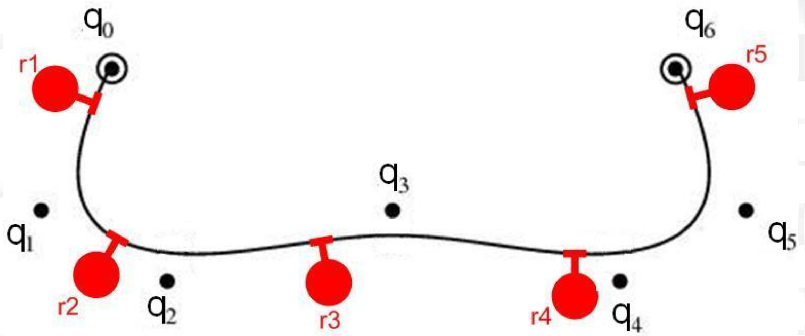
Configuration defined by B-splines

$$h=[p, U, U_r]$$

where:

- **p** is the control point vector of the hose B-spline model.
- **U** is the vector of knots in the B-spline model.
- $\mathbf{U_r}$ is the robots knot vector.



$$q(u_{r_i}) = \sum_{i=0}^{n} N_i(u_{r_i}) \cdot p_i = r_i, \forall i \in [0, L]$$

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Control of Linked MCRS

Linked MCRS control

- We define two basic kinds of hose positioning task:
  - Bring the hose from an initial configuration to a final configuration.
  - Given a sequence of hose configurations, the system must follow it in order to accomplish the transport of the hose.

Transitions among configurations

We want to obtain the motion of the attached robots which will move the hose from the initial hose configuration to the desired configuration.

$$\boldsymbol{p}_0 \longrightarrow \boldsymbol{p}_*$$

Linked MCRS control

Transitions among configurations

Configuration error

$$e(\boldsymbol{p}) = (\boldsymbol{p}_* - \boldsymbol{p})^2$$

Proportional control law on the control points

$$\dot{\boldsymbol{p}} = k(\boldsymbol{p}_* - \boldsymbol{p})$$

Linked MCRS control

Transitions among configurations

- We derive the control points velocities and use the desired control points accelerations in the matricial Lagrange equation in order to obtain the required external forces F that robots must generate in the control points.

$$\widehat{F}_p = M\hat{A} - P - F_e$$

Linked MCRS control

Transitions among configurations

- From an inversion of the hose model we obtain the forces that robot must exert F_r in order to obtain the required external forces in the control points F_p.

$$\widehat{\boldsymbol{F}}_{\boldsymbol{r}} = J_{pr}^{+} \cdot \boldsymbol{F}_{\boldsymbol{p}}$$

Linked MCRS control

Transitions among configurations

- Applying the obtained robot forces in the direct model we obtain the control points accelerations $\hat{A}$.

$$M\hat{A} = F_e + P + J_{pr} \cdot \hat{F}_r$$

- Then we obtain the robots accelerations

$$\widehat{A^r} = J_{pr} \cdot \hat{A}$$

- Finally, integrating the robots' accelerations $\widehat{A^r}$ we obtain the robots velocities.

Linked MCRS control

Following a sequence of intermediate configurations

We interpolate the sequences of configurations $\boldsymbol{h}_k$ by a clamped B-interpolating curve

$$\boldsymbol{\phi}(\xi),\ \xi \in [0,1] \qquad \boldsymbol{\phi}(0) = \boldsymbol{p}_{\mathbf{0}},\ \boldsymbol{\phi}(1) = \boldsymbol{p}_{*}$$

We follow continuously the interpolating curve by a mean velocity close to $\boldsymbol{v}_{ref}$.

$$\dot{\boldsymbol{p}} = k \cdot [\phi(f(v_{ref}, \boldsymbol{p})) - \boldsymbol{p}]$$

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Linked MCRS control heuristic

Follow the leader approach

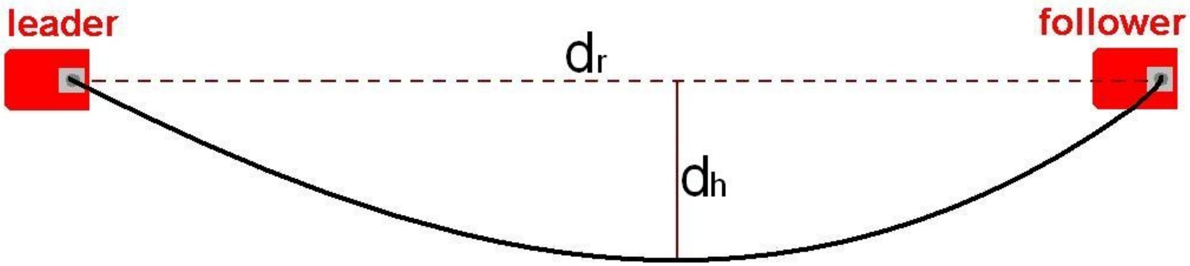
From a given trajectory for the leader robot the remaining of the robots must follow it in order to accomplish the transport of the hose.

- We accomplish this task by taking into account:
  - The passive element state (curvature of the hose segments).
  - The distances between consecutive robots.
- In order to define the heuristic, we make the following assumptions:
  - If a pair of robots are too close, the hose segment between them will describe a curve.
  - If a pair of robots are sufficiently separated, the hose is stretched and approximated to the straight line between the robots.

Follow the leader approach

The curvature of a hose segment is indirectly measured as:

$$c = \frac{d_h}{d_r}$$



We define a maximum $\overline{c}$ and minimum $\underline{c}$ segment curvature for the transport of the hose and three speed levels w_1, w_2 and w_3.

Follow the leader approach

Rules for determining the robots speed

if $c_i < \underline{c}$ then

$$w_{i+1} = w_2$$

else

if $c_i > \bar{c}$ then

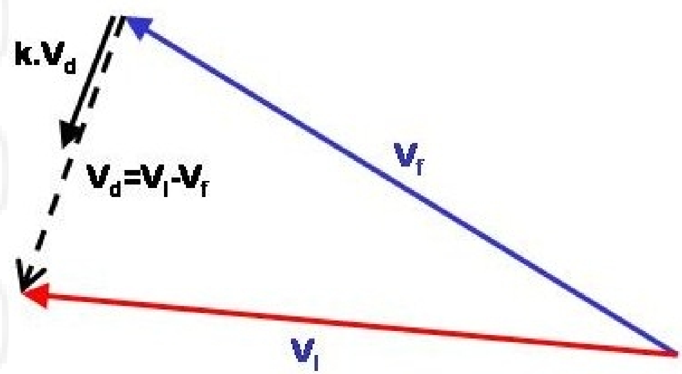
$$w_{i+1} = w_0$$

else

$$w_{i+1} = w_1$$

Follow the leader approach

Robots' orientation



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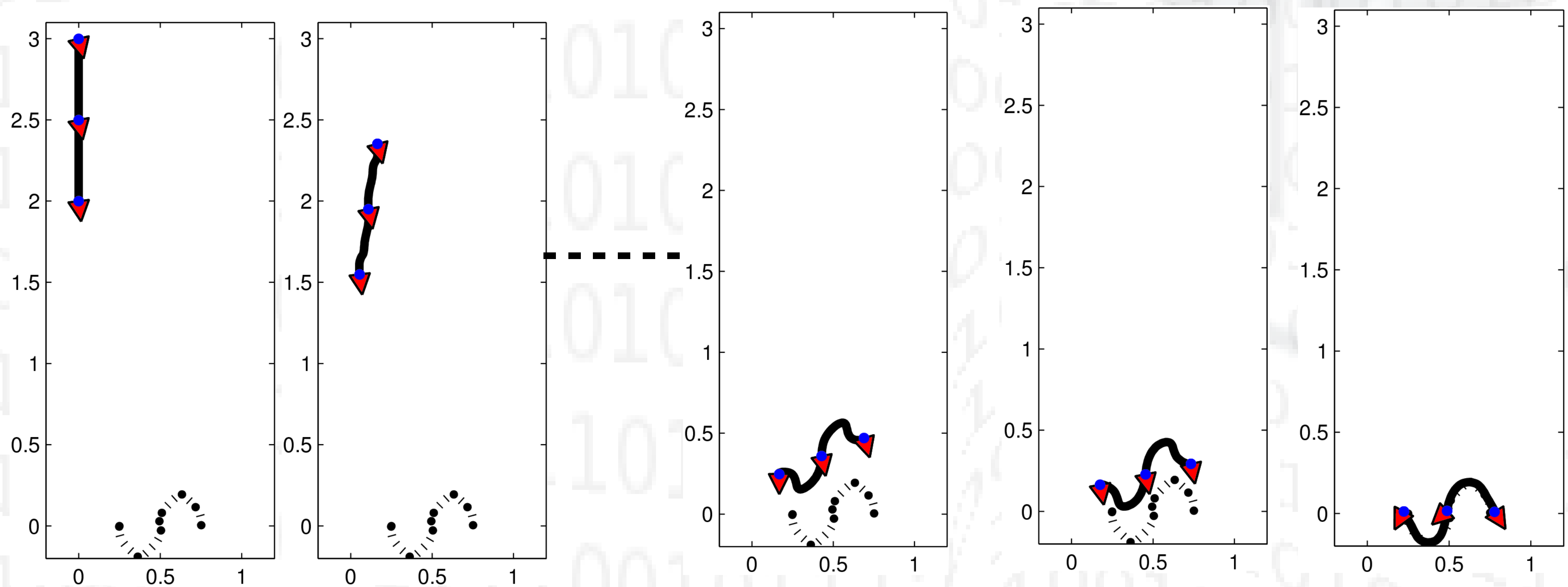
Control of Linked MCRS

Simulation

Transitions among configurations

Not taking into account the hose dynamics

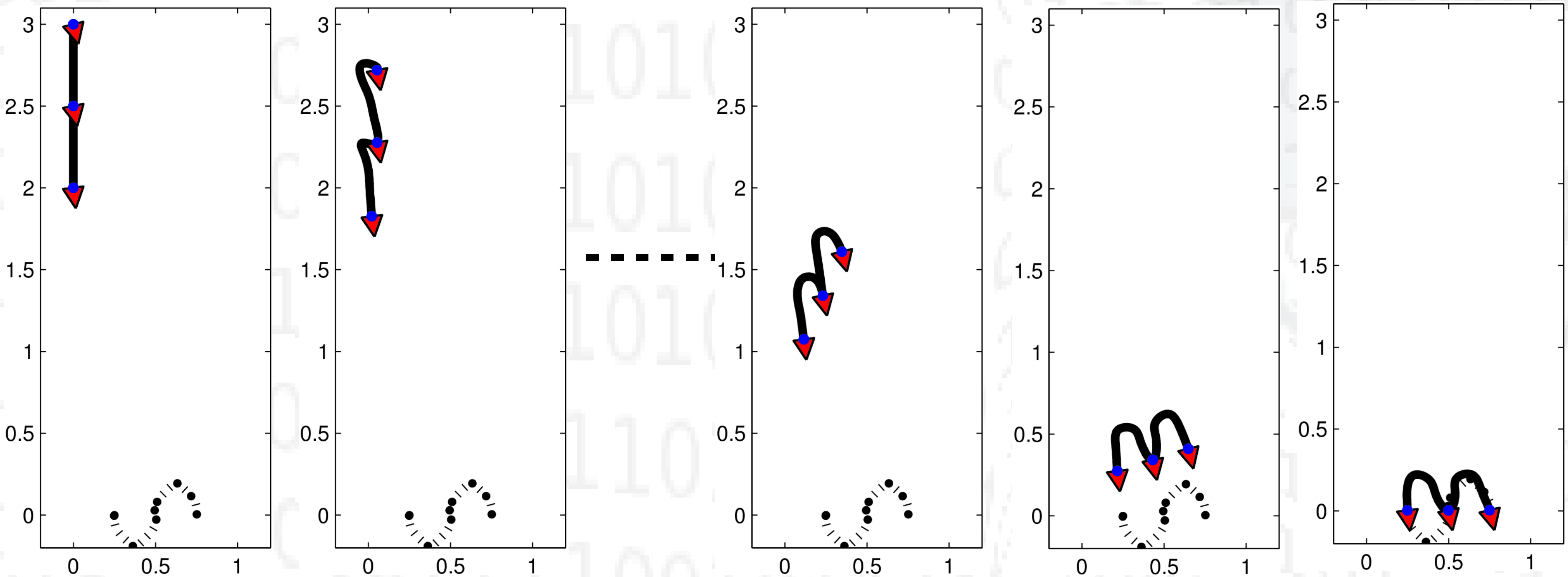


Control of Linked MCRS

Simulation

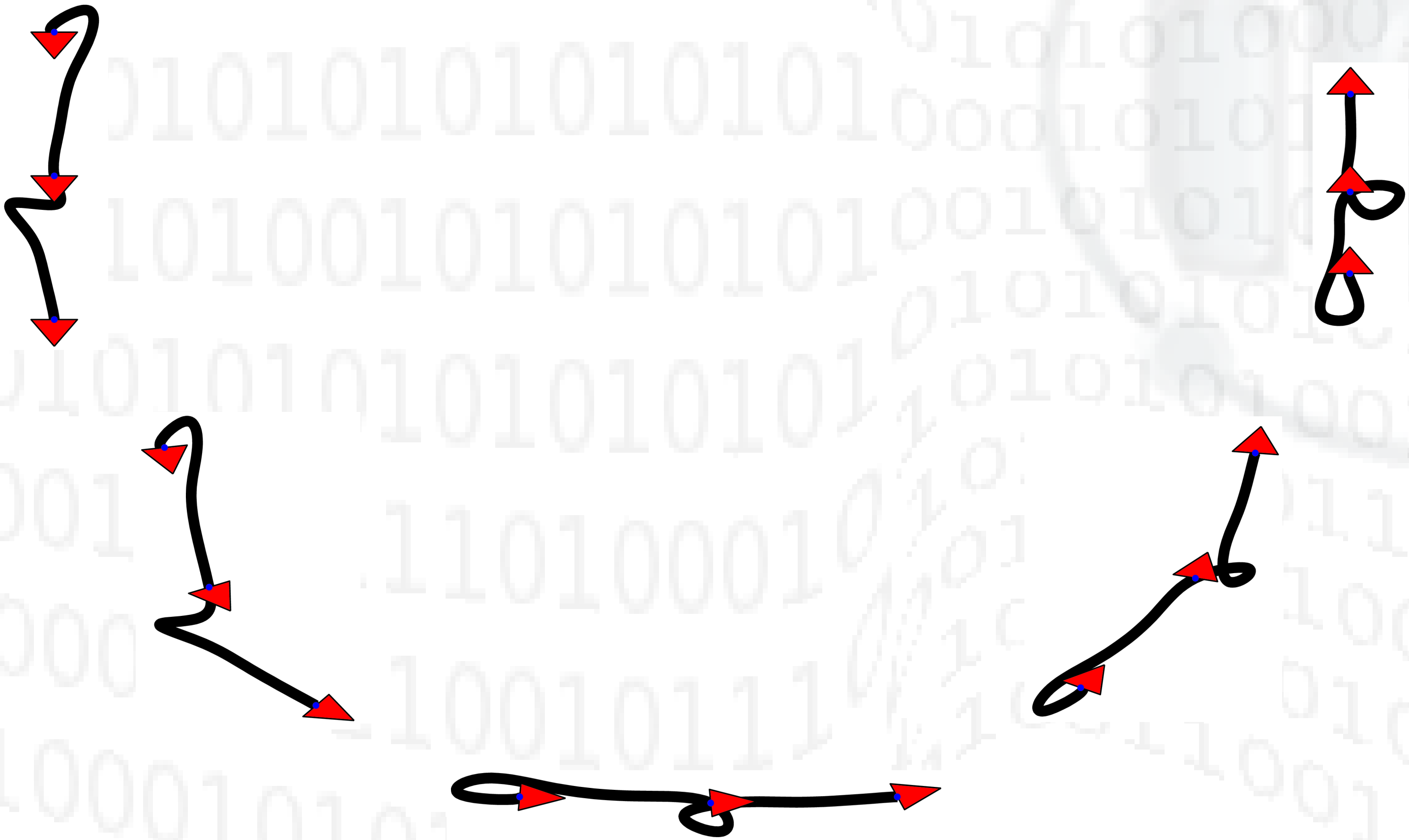
Transitions among configurations

Taking into account the hose dynamics



Hose transportation

Sequence of the trajectory



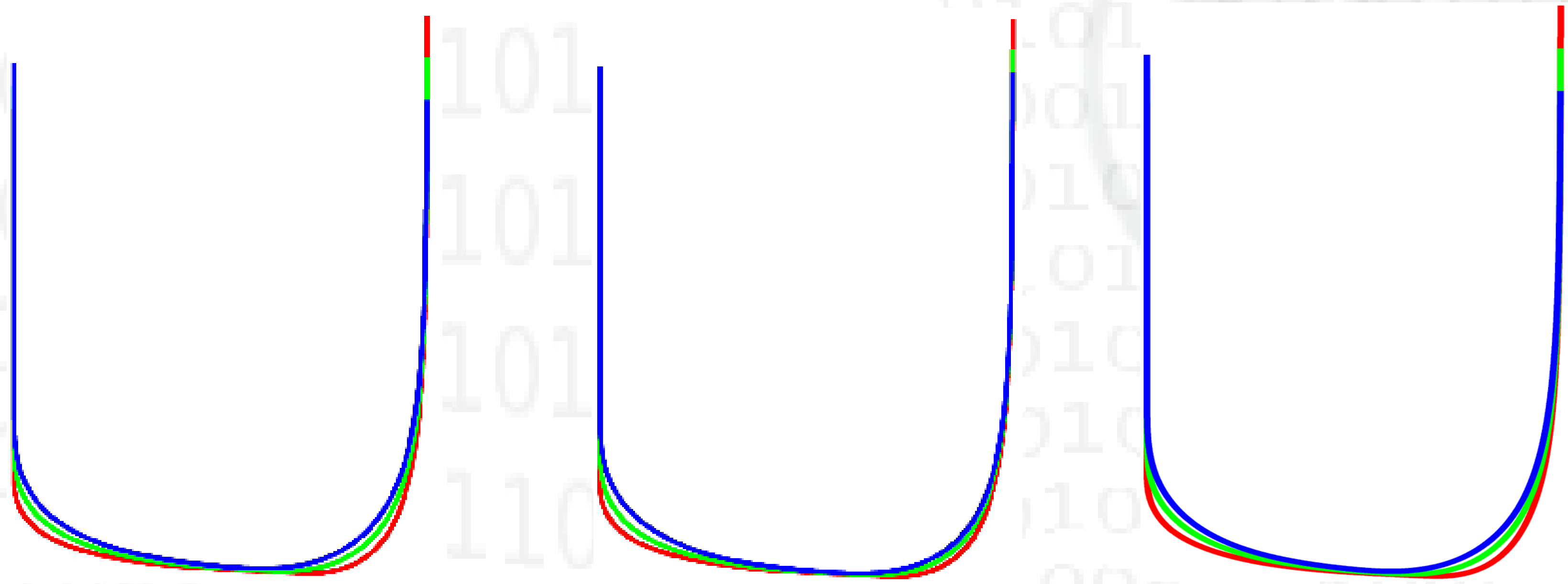
Control of Linked MCRS

Simulation

Video

Hose transportation

Validation of control approaches



Distance based | Segment based | Configuration sequence

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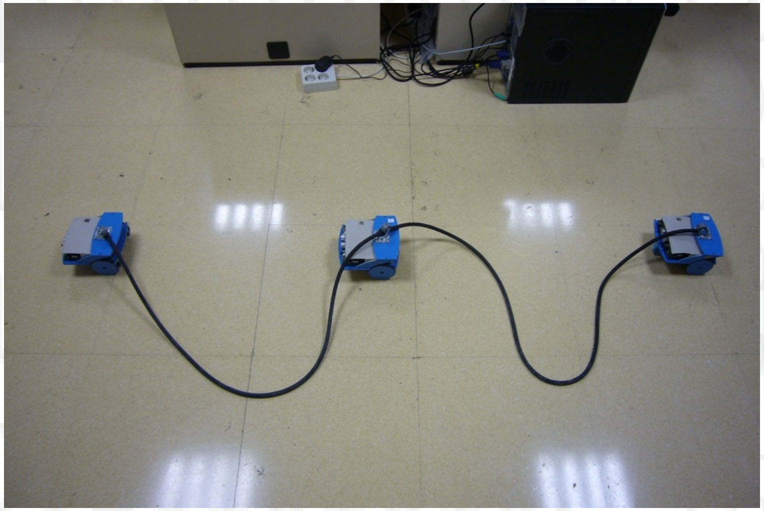
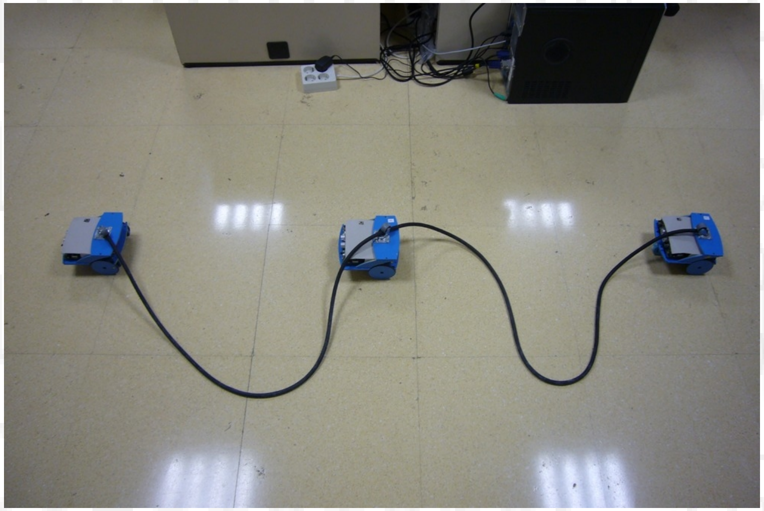
Real life experimentation

Definition



- Basic trajectory for the leader as a straight line.
- Segment curvature based approach.
- Approach to Position based Visual Servoing.
- Fixed camera in a zenith position.
- The Control process is centralized in a master computer.
- Master-slave communication via radio-modems.

Starting conditions

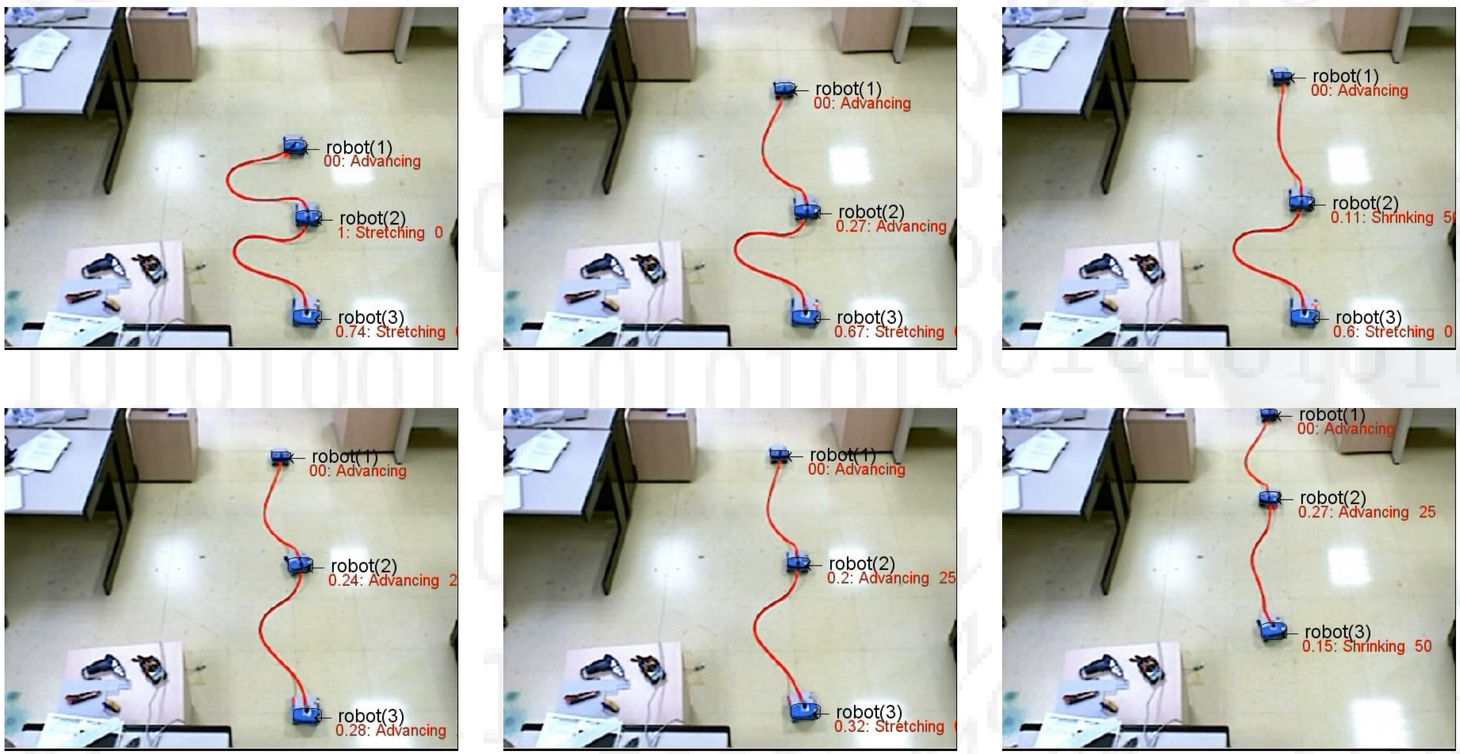


- Hose of 2 meters in length.
- $\underline{c}$ = 0.15
- $\overline{c}$ = 0.30
- w_1= 0 cm/s
- w_2= 10 cm/s
- w_3= 20 cm/s.

- Robots are roughly aligned in the direction of advance.
- Robots have similar orientations.
- Hose can be bended but allowing the robots advance.
- The area in which robots will move must be obstacle free.

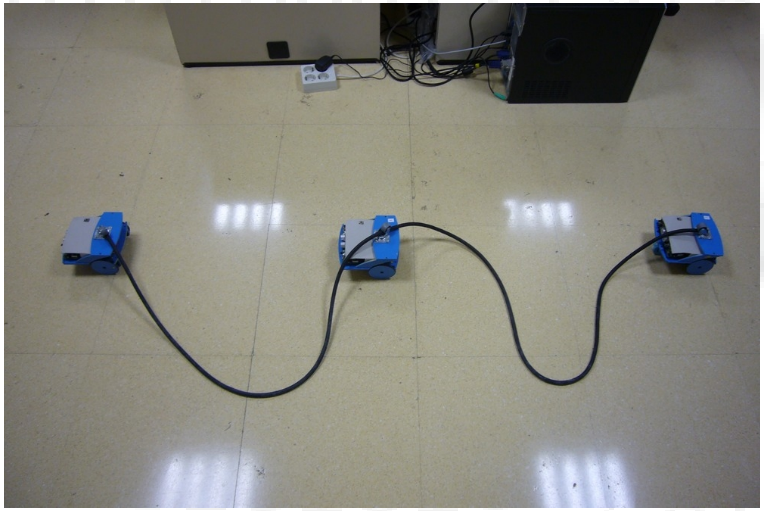
Control of Linked MCRS

Real life experimentation



Control of Linked MCRS
Real life experimentation

Video



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Control of Linked MCRS

Conclusions

- We have realized a Linked MCRS, opening a whole area of research, showing behaviors that clearly separate it from others kinds of MCRS.
- We have built a geometrical and dynamical model of a Linked MCRS for the transport of a hose, based on the formalism GEDS.
- We have formally derived inverse kinematics/dynamics control rules.

Conclusions

- We have developed a simulation system in order to:
  - Test the formally derived control algorithms.
  - Test heuristic control algorithms.
  - Reproduce some physical phenomena.
- We have built a physical realization of the system, using a centralized Visual Servoing approach.

Conclusions

- Future work lines
  - Simulations and physical realization of distributed control approaches.
  - Automated identification of the hose parameters.
  - Solve the problems of local minima for the control of the hose by techniques as Particle filter.

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Summary of Conclusions

We have worked on visual Servoing applications for two widely different fields of robotics:

- Legged robots (Aibo):
  - To obtain fast reactive behavior involving all their degrees of freedom.
- Linked Multi Component Robotic Systems:
  - To be able to implement control heuristics on it.

Summary of Conclusions

For the legged robots (Aibo) we have succesfully:

- Formulated a direct kinematics model from its structural description.
- Proposed an inversion model which includes stability constraints.
- Tested empirically the advantages and limitations of the approach.

Summary of Conclusions

Further work for the legged robots visual servoing:

- More extensive experimentation of the real robot.
- Integrate data induction algorithms into the model (Artificial Neural Networks) to improve its robustness.

Summary of Conclusions

For the Linked MCRS we have successfully

- Proposed a formal direct kinematics model encompassing the passive linking element (the hose).
- Proposed an inversion model that would give the control commands for the robot.
- Perform simulations assessing the expected behavior of the system.
- Test heuristic control strategies:
  - In simulation.
  - On a physical realization.

Summary of Conclusions

Further work on Linked MCRS may address:

- Testing heuristic and formal control approaches under:
  - An extensive simulation exploration of the system's behavior.
  - More extensive physical experiments.
  - Other system embodiments (e-puck robot).

Thank you for your attention