Image-based coordinates for rigid motion

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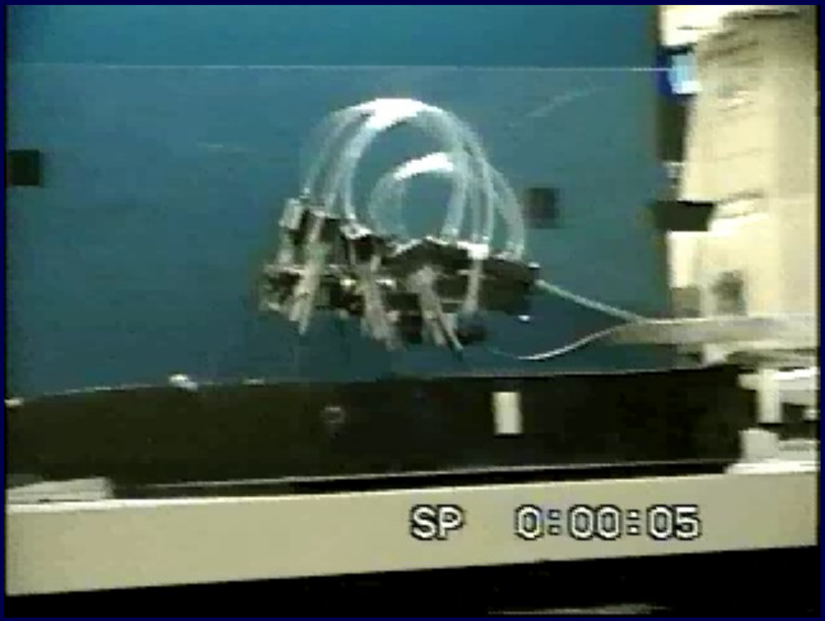
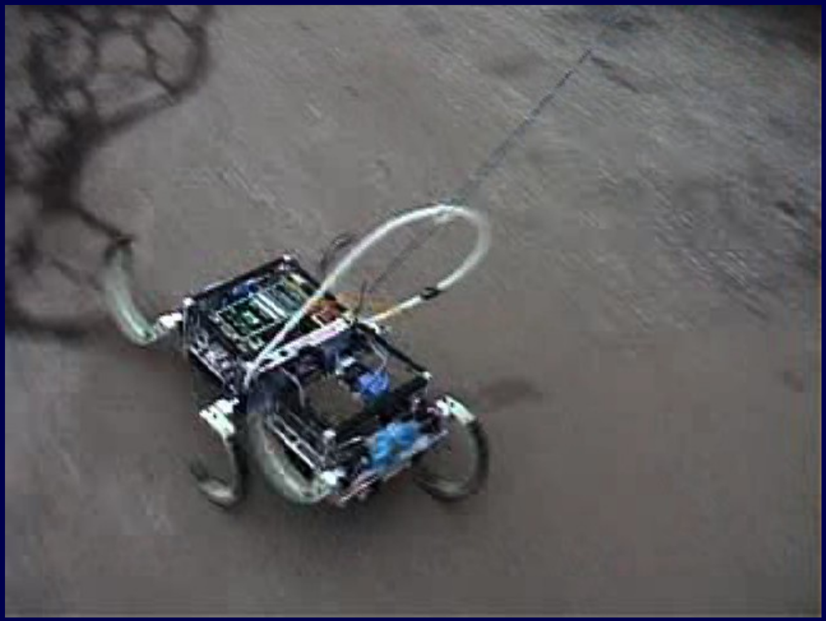
Abstract

A collection of novel coordinate transformations from a robot's task space (e.g. $\mathrm{SE}(3)$) to a sensor-space enables the construction of globally convergent, fully sensor-based, dynamic servoing systems that keep measurements within full "view" of the sensor suite.

Motivation: Two Dynamical Legged Robots



Sprawl running on a treadmill.



RHex running outdoors.

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  - ⋆ convergence: only a handful of algorithms with provable convergence
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- RHex and Sprawl

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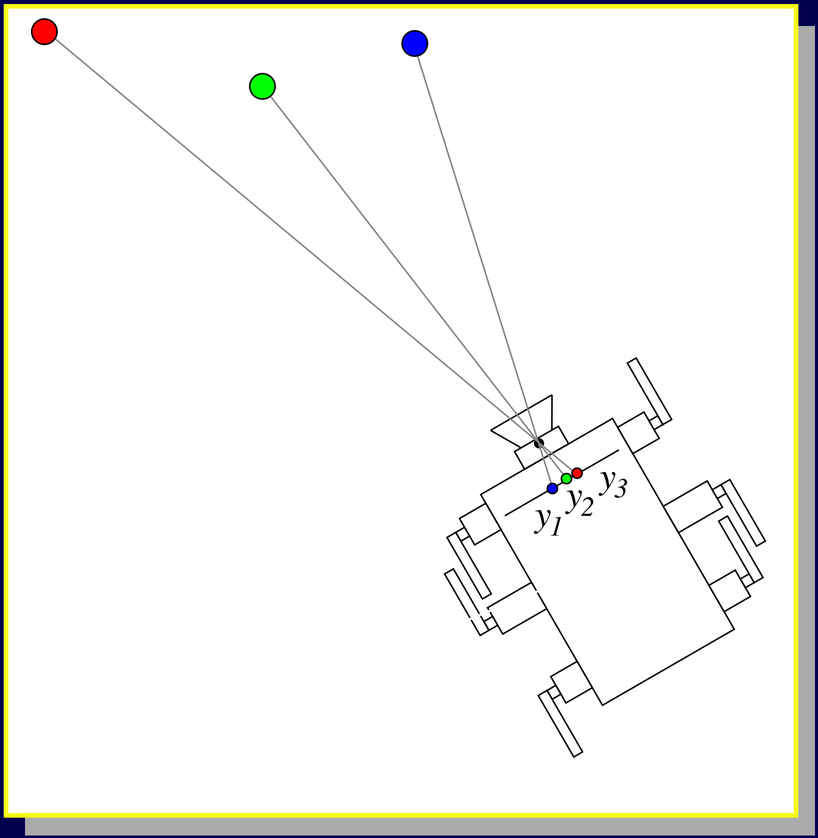
- RHex and Sprawl
  - ⋆ are highly stable, fast, dynamical platforms
  - ⋆ exhibit stable locomotion highly dynamical running
  - ⋆ can generate “second order” turns while running (not kinematic turns)
  - ⋆ cannot run “sideways,” i.e. they are nonholonomically constrained

Visual Servoing: Basic idea

Given

- robot: $q \in \mathbb{R}^n$



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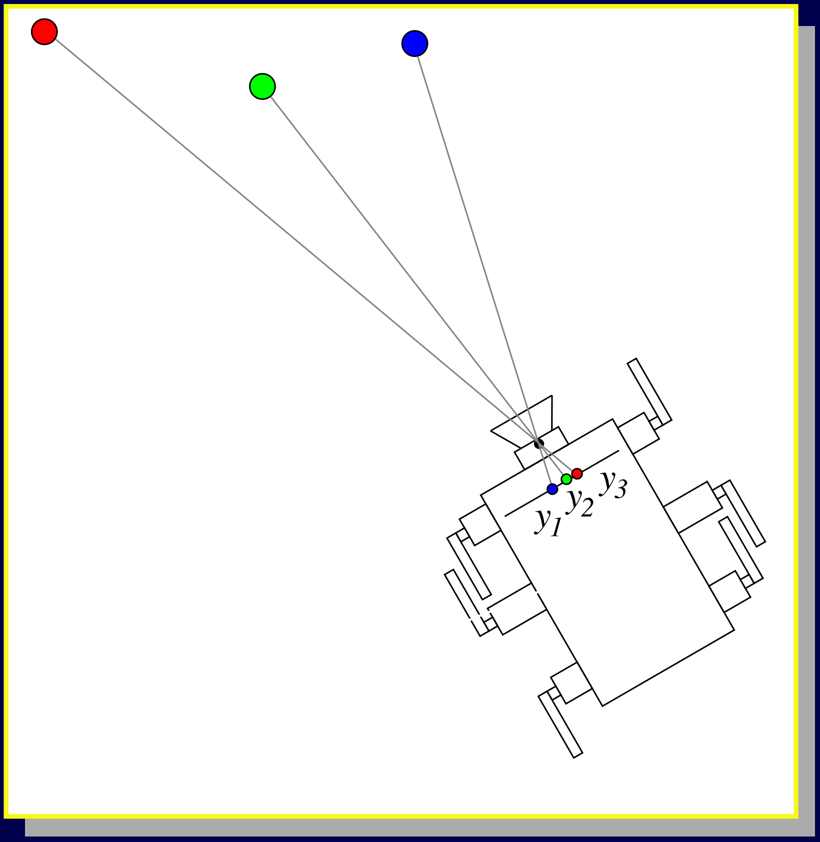

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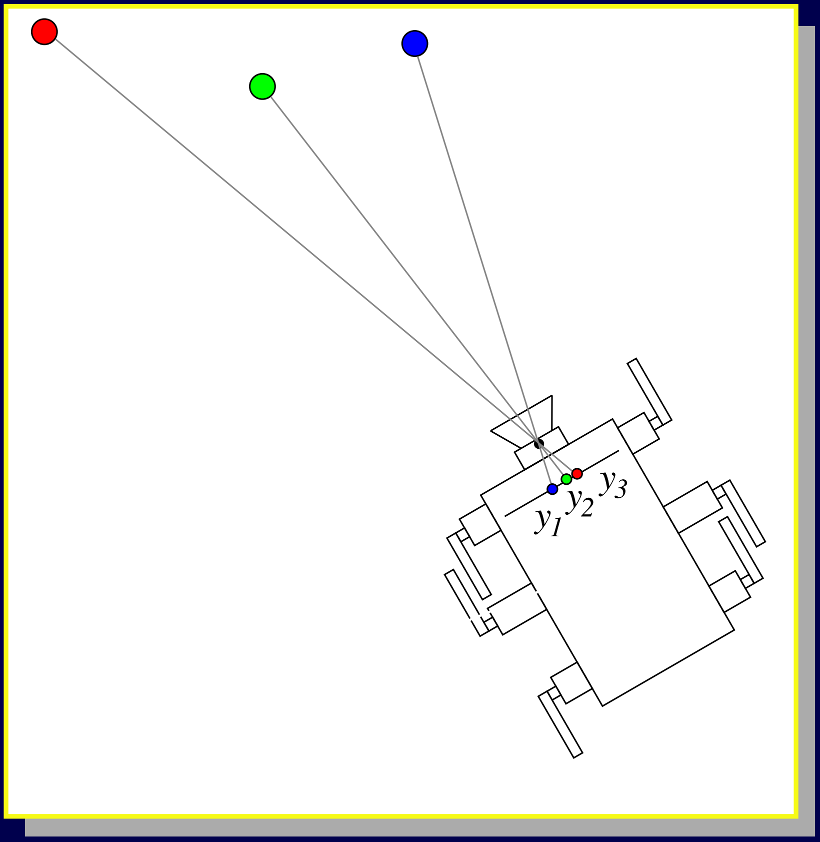

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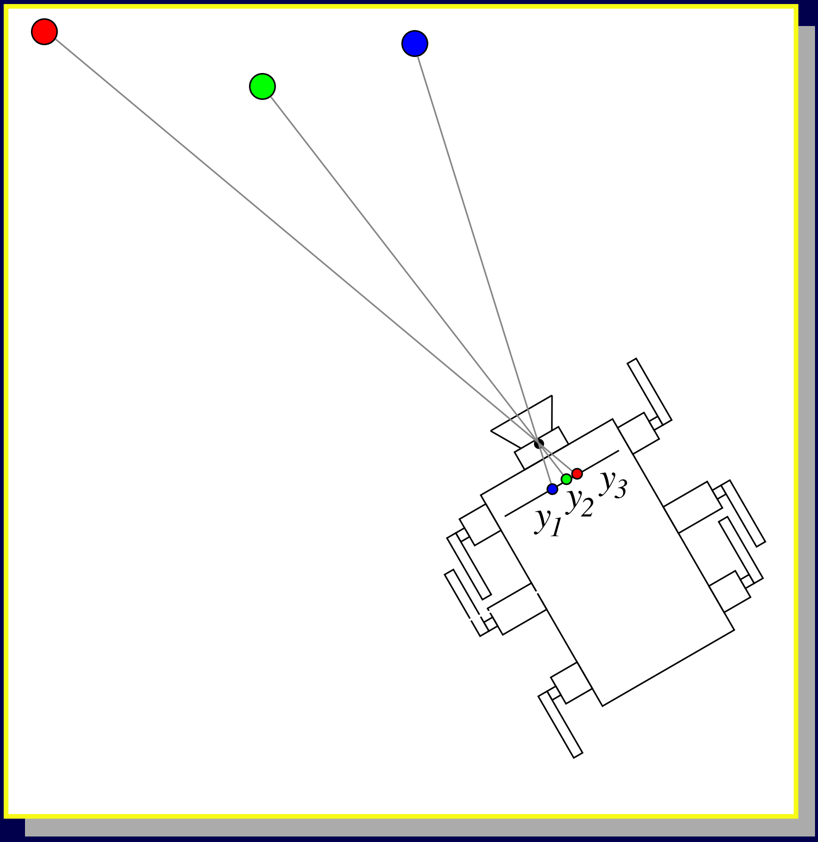

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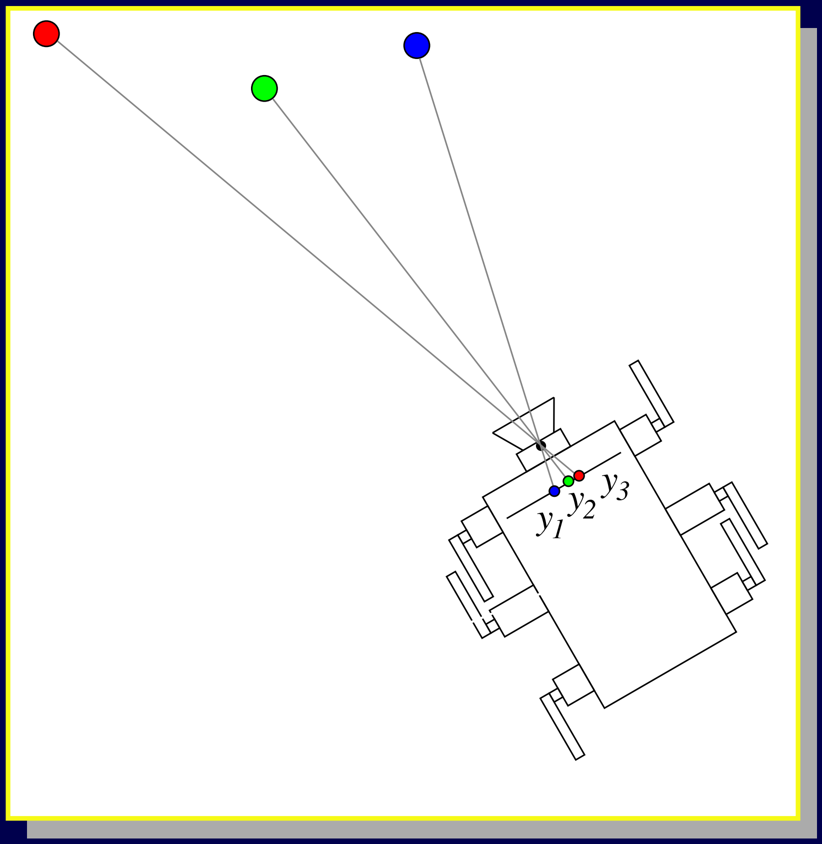
Objective

- move robot to align current view with a “goal” image, namely $y \to y^*$ as $t \to \infty$



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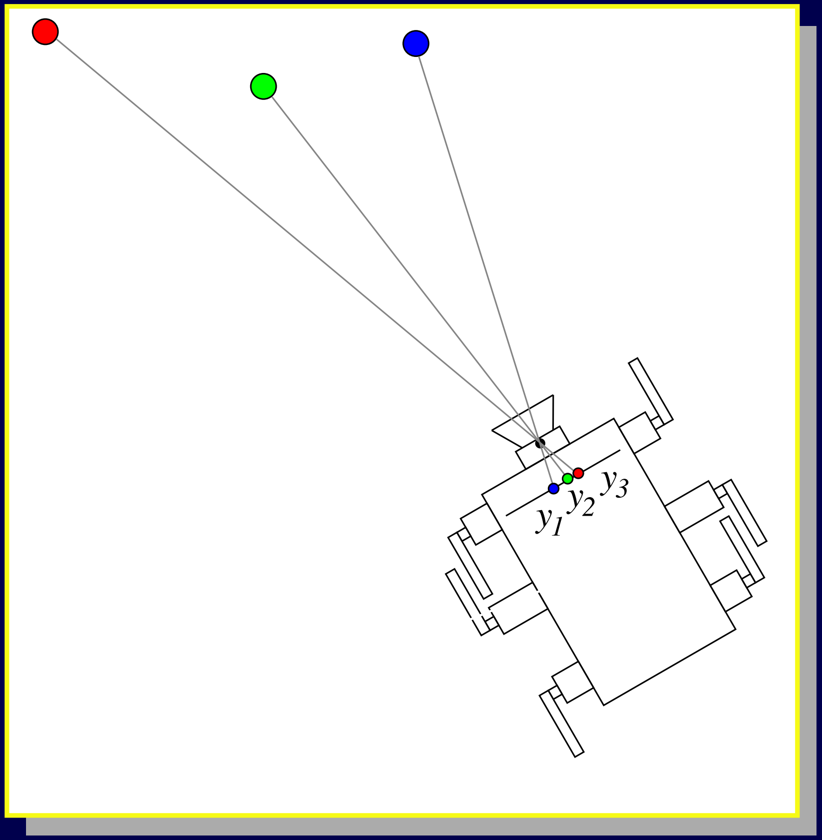

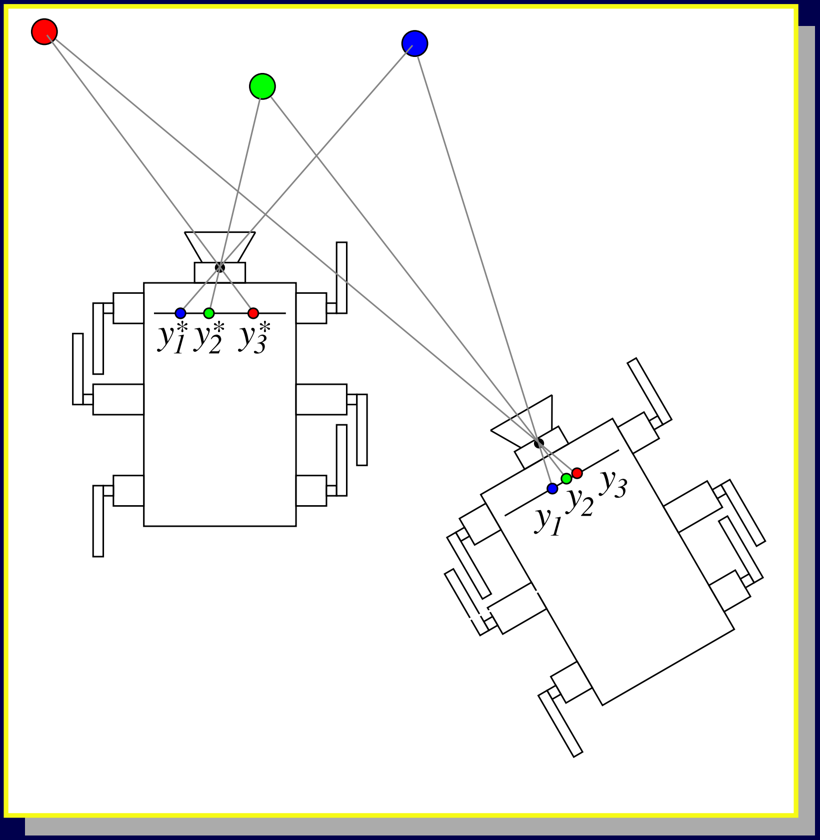

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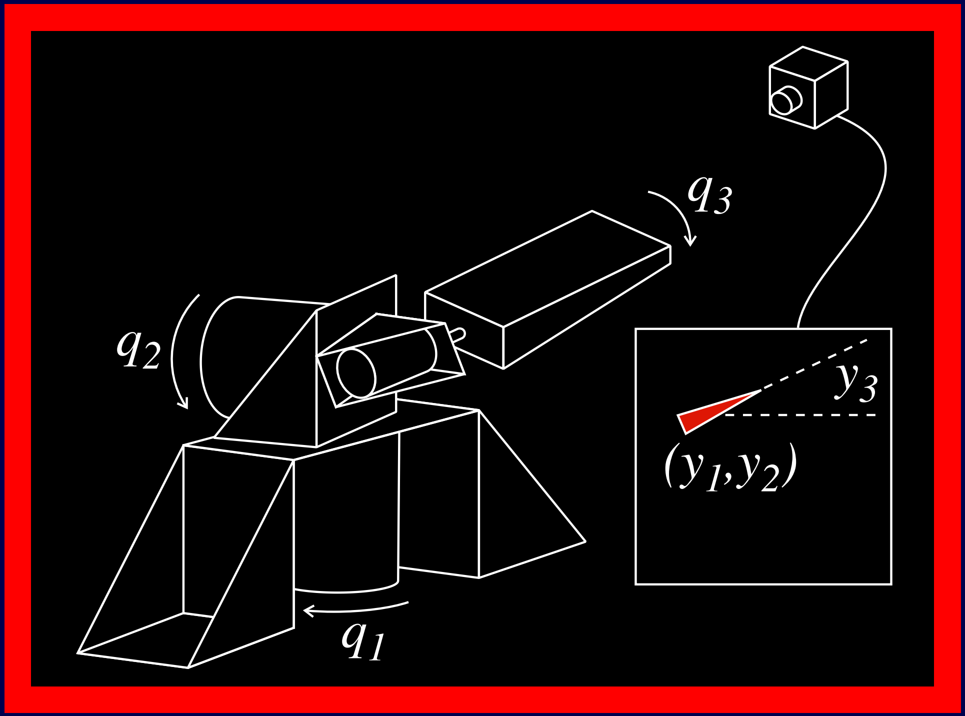
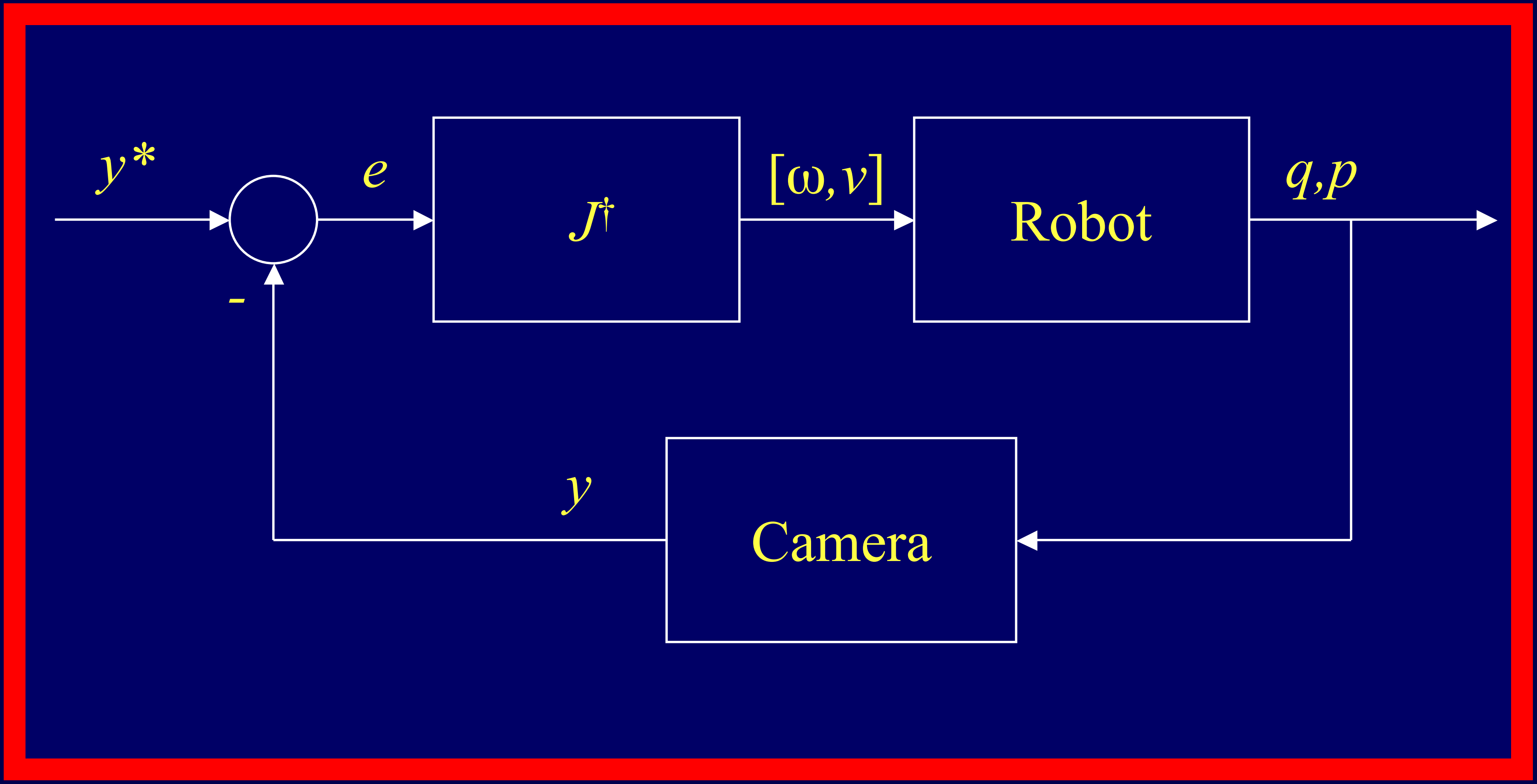
- In the *fixed camera* setup, the robot moves in front of stationary camera



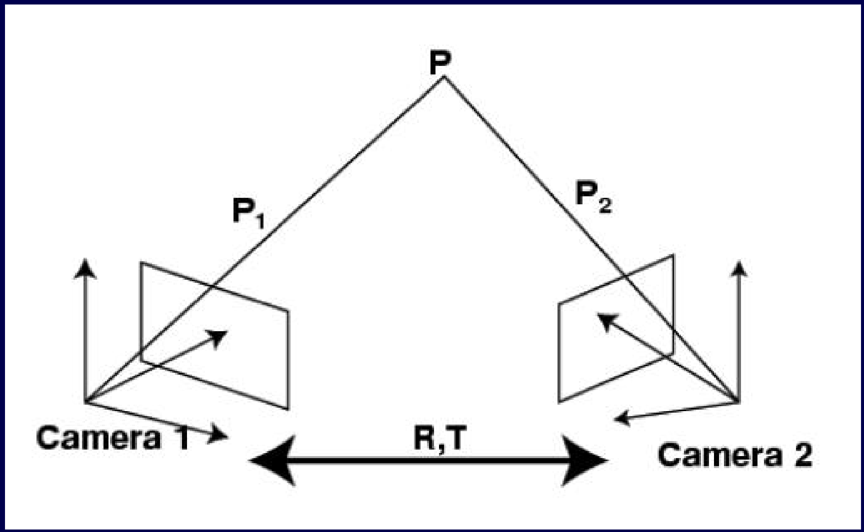
Visual Servoing: Traditional Approach



[Hutchinson, Hager, Corke 96] [Hill & Park 79]

Visual Servoing: State-of-the-Art

- dynamical blimp servo [Zhang & Ostrowski, 99]
- global partial pose servo [Taylor & Ostrowski, 00]
- 2 1/2 D servo [Malis, et. al., 99]
- partitioned visual servo [Hutchinson & Corke, 01]
- epipolar servoing [Prattichizzo et. al, ’02]



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- often the coordinates are hand picked, e.g. joint angles of a robot, or the position and orientation (x, y, θ) of a body in the plane
- equations of motion, i.e. *Lagrange's Equations*, are expressed

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} - \frac{\partial L}{\partial q_i} = \tau + F_{\text{ext}} \qquad \Longrightarrow \qquad M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = \tau + F_{\text{ext}}(q, \dot{q})$$

where $L(q, \dot{q}) = \text{KE} - \text{PE}$ is the *Lagrangian*, where $\text{KE} = \dot{q}^T M(q)\dot{q}$ is the kinetic energy and PE is the potential, and $G(q) = \nabla_q \text{PE}$. F_{ext} represents "non energetic" forces (e.g. friction), and τ is a torque input vector.

Example Lagrangian systems

- mass-spring-damper;
  - $q = x$ is the position of the mass
  - $\mathrm{KE} = \frac{1}{2} M \dot{x}^2 \implies C = 0$
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- dynamical equations

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$$u = -\nabla\varphi(q) - B(q,\dot{q})$$

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- In general, the system will converge to the minima of φ

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- If $y = g(q)$, then there are as many DOF's of y as there are of q

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  - ⋆ g is just a similarity transform!

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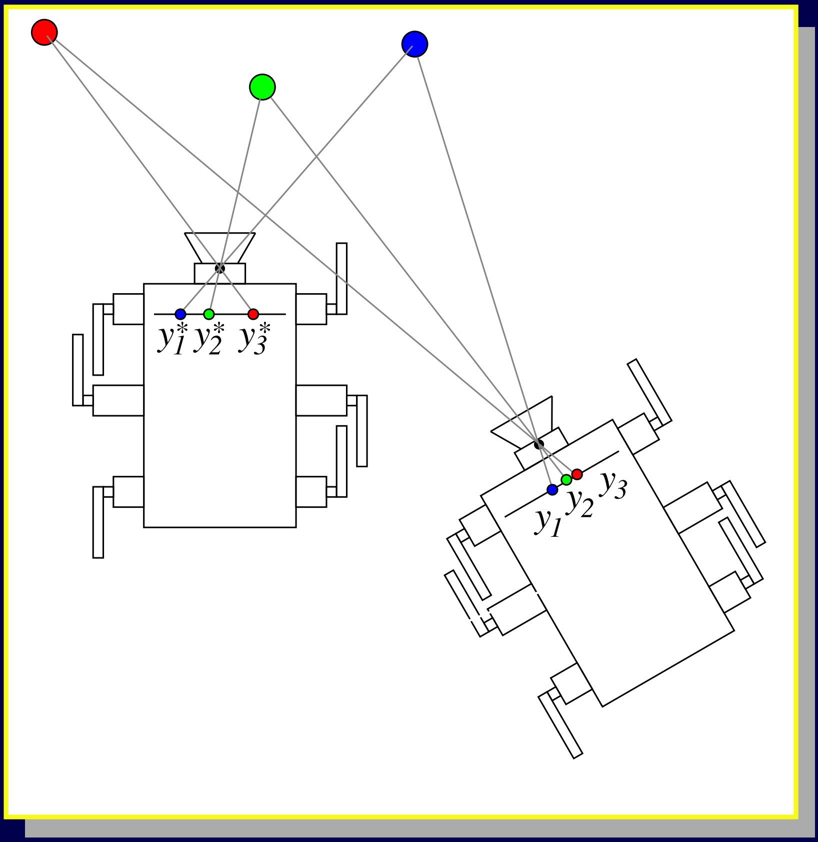

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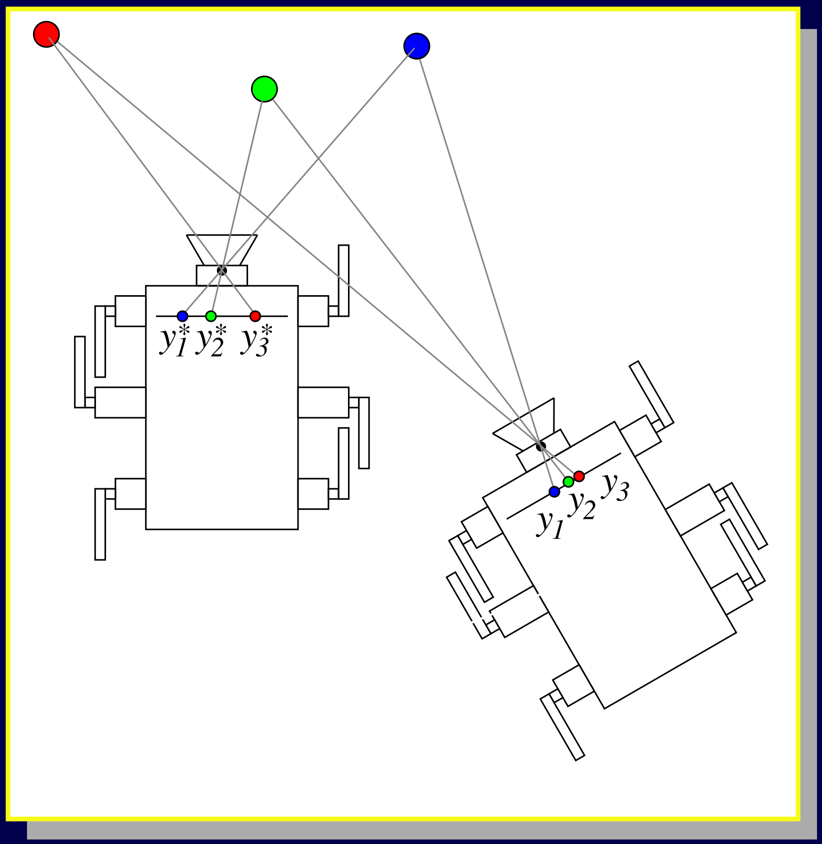

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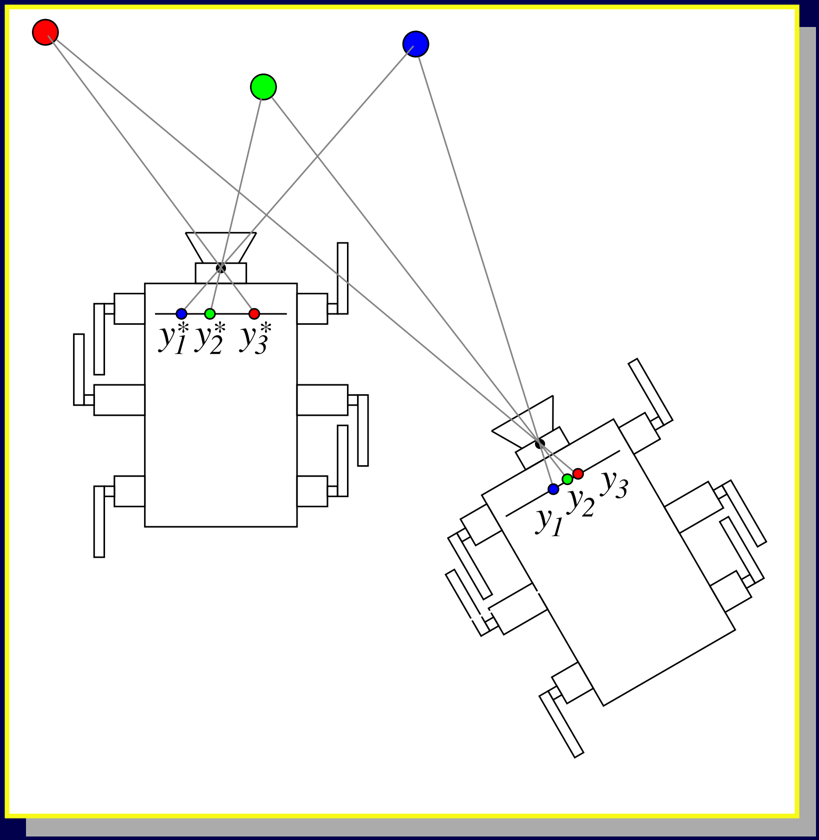

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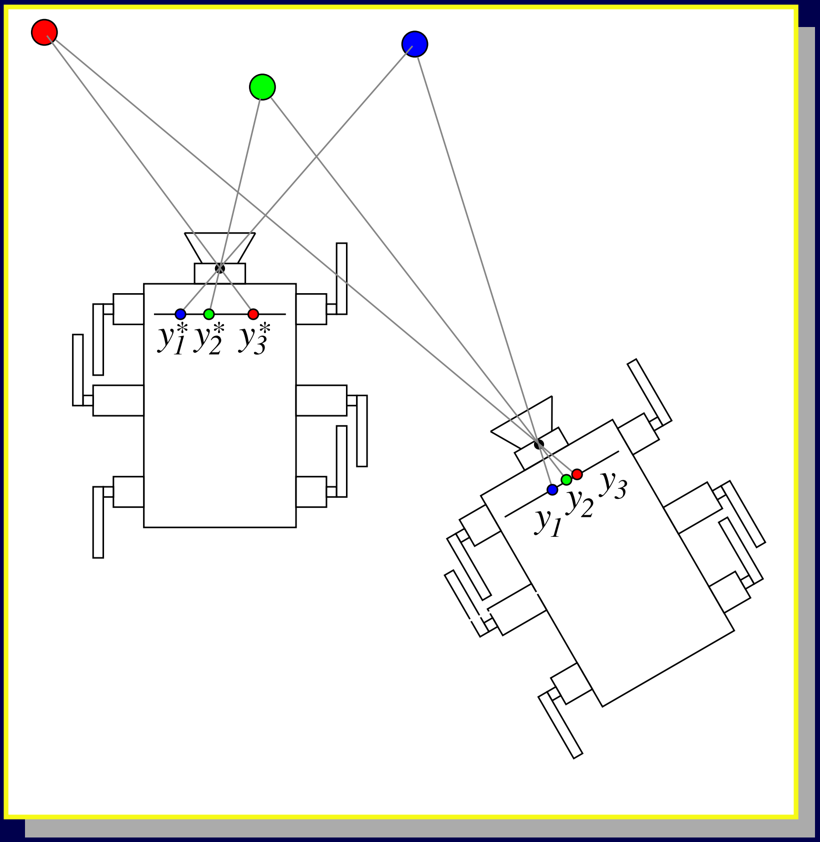

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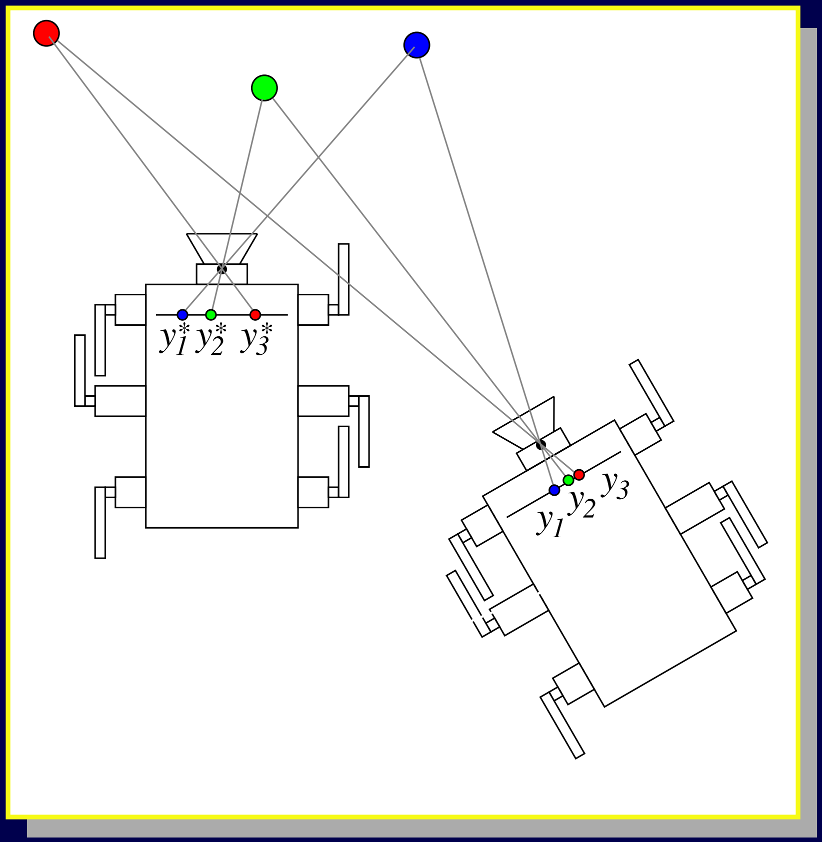

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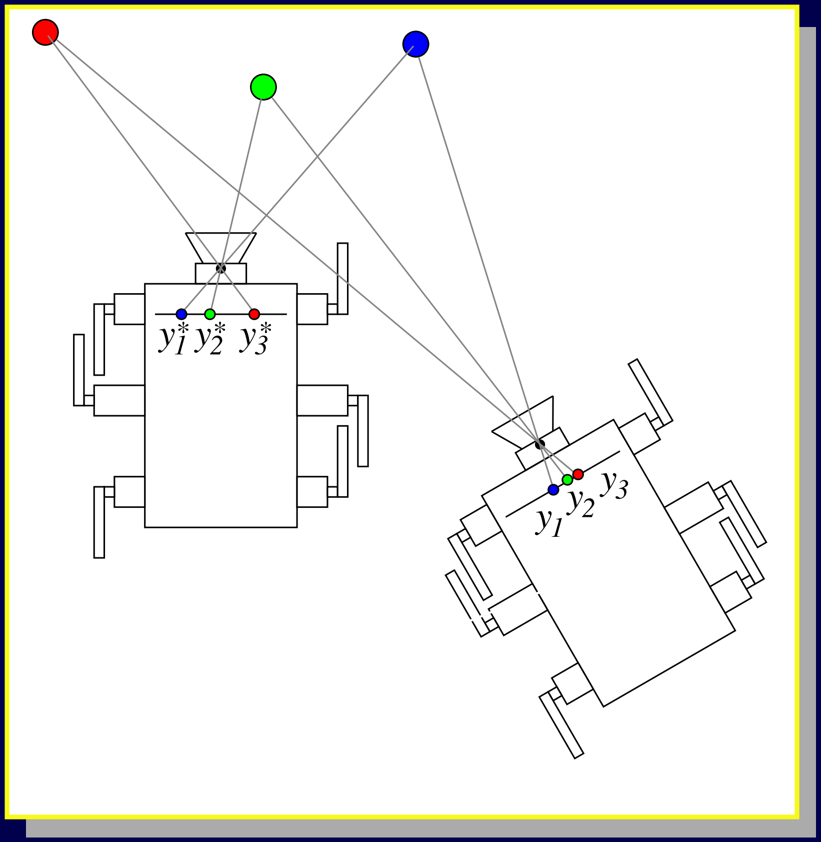
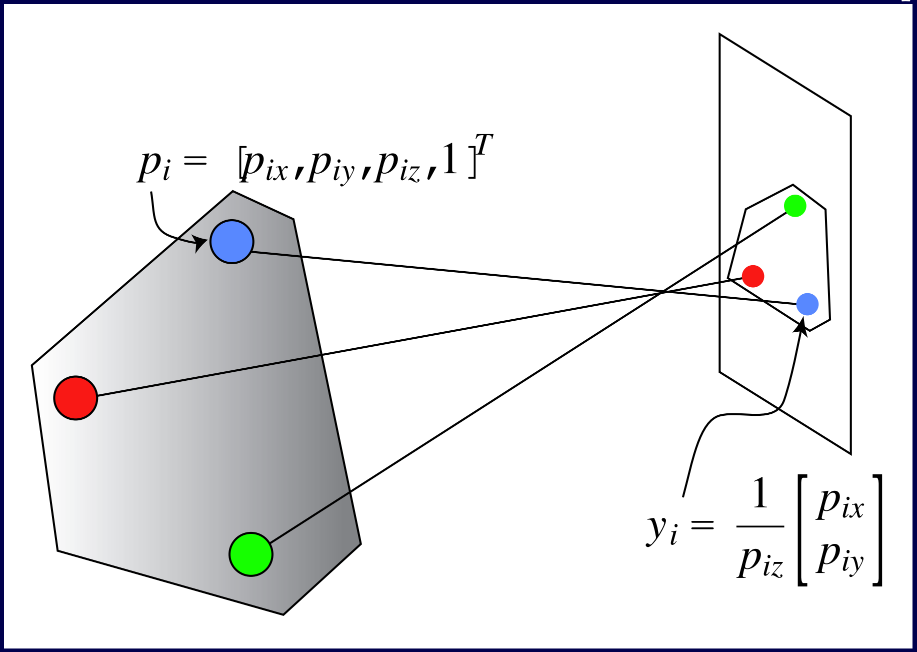


When is c *just a change of coordinates?*

The usual definition of c

- c maps rigid transformations to image feature locations. It is composed from the action of $\mathrm{SE}(3)$ on $\mathbb{R}^3$ and perspective projection, as follows.

- The camera is a perspective projection camera, and thus if $p = [\ p_x,\ p_y,\ p_z,\ 1\ ]^T$ is a point in space then $y = \pi(p) := \frac{1}{p_z}[\ p_x,\ p_y\ ]^T$



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- In the camera frame, $P = HB$, where $P = [p_1, p_2, \ldots, p_n]$ and $p_i = [\ p_{xi},\ p_{yi},\ p_{zi},\ 1\ ]^T$.

- Rigid body motion given by

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- The camera map, $c : \mathrm{SE}(3) \to \mathbb{R}^{2n}$ is the given by $c : H \mapsto Y$.

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$$H = \begin{bmatrix} R & T \\ 0^T & 1 \end{bmatrix} \in \mathrm{SE}(3)$$

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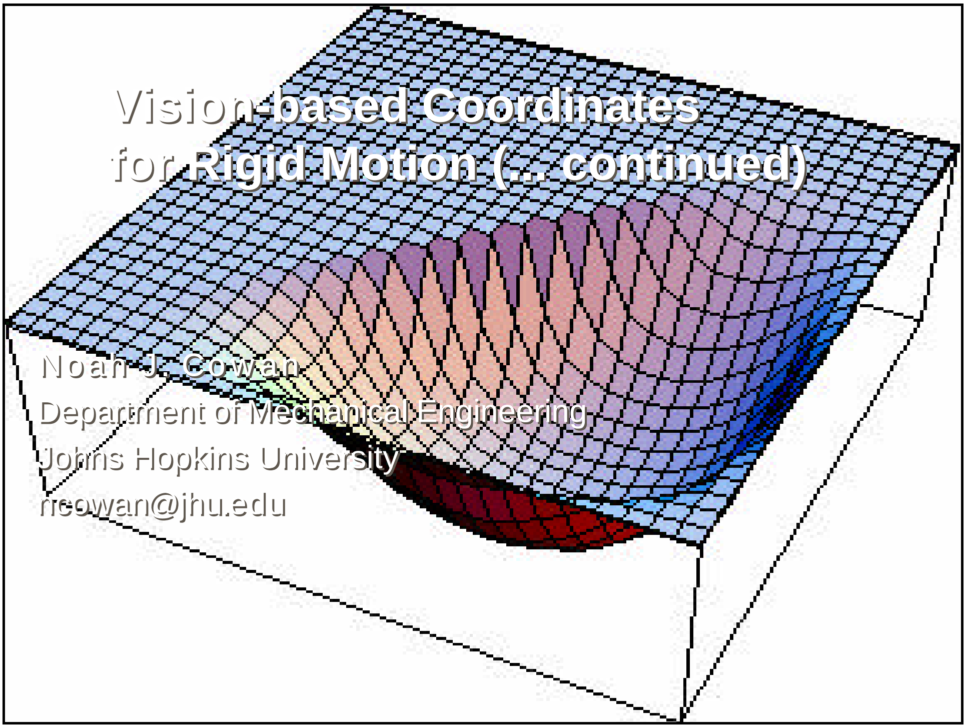
- Note that, in general $\dim \mathrm{SE}(3) \neq 2n$ except when $n = 3$. In this case c is not into!

to be continued...

Click here to continue: Presentation continued in Power Point



Vision-based Coordinates for Rigid Motion (... continued)

Noah J. Cowan
Department of Mechanical Engineering
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[Cowan et. al., ICRA '99; TRA '02]

Image-based coordinates: 2D world

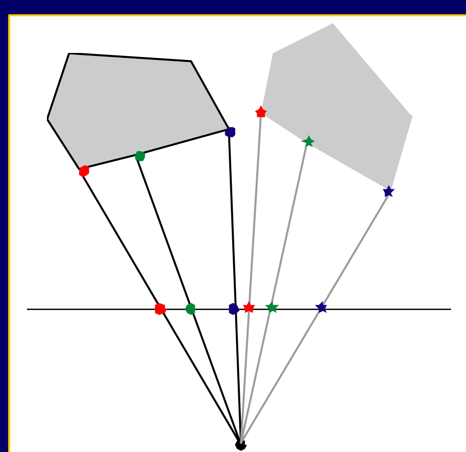
Planar body, $H \in SE(2)$

Collinear features

Pinhole camera (calibrated perspective projection)

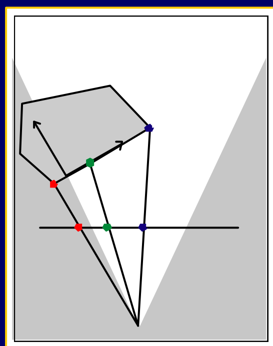
Output $y = c(H) = [y_1 \quad y_2 \quad y_3]^T$

Goal $y^* = c(H^*)$

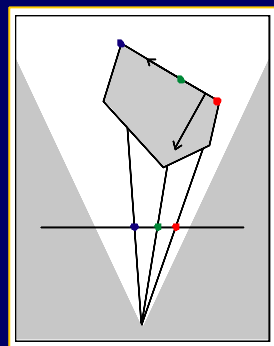


Planar Servoing: visibility

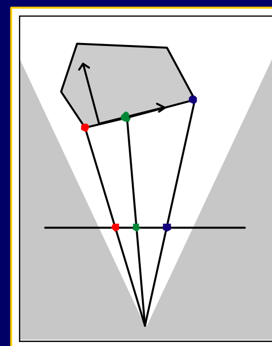
Facing camera, out of FOV



In the workspace, but self-occluded



All features visible, *V* Ì SE*(2)*



Planar Servoing: image coordinates

- The camera map $y=c(H)$ is a *diffeomorphism*

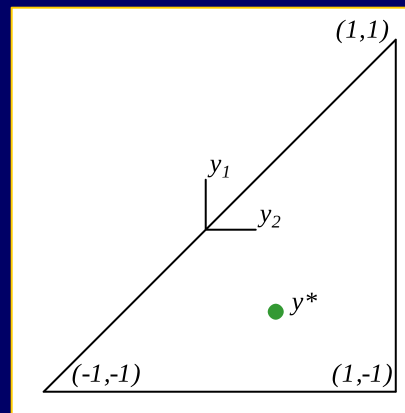
variables to the image plane!

The visibility obstacles appear as the boundary of this simple set!

Planar Servoing: key observations

- The image space is independent of parameters
- We can use image plane coordinates to design a global, dynamical occlusion-free controller

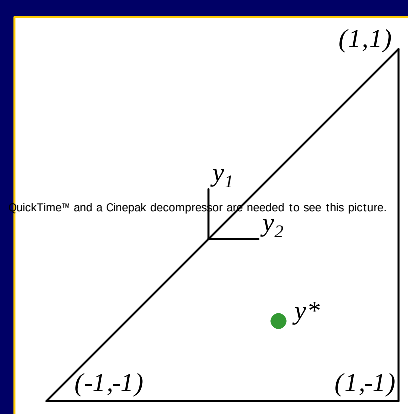
$Z = \{-1 < y_1 < y_2 < y_3 < 1\}$



Planar Servoing: solution

- We would like a controller to keep us within Z
- "Navigation function" for planar visual servoing is simple!

$Z = \{-1 < y_1 < y_2 < y_3 < 1\}$



Planar Servoing: solution

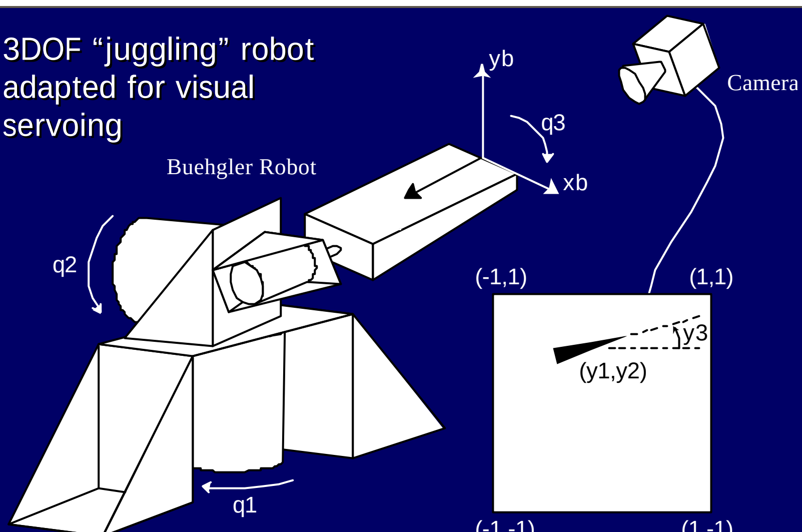
- We would like a controller to keep us within Z
- "Navigation function" for planar visual servoing is simple!
- Resulting controller is global, dynamic and occlusion-free

$$Z = \{-1 < y_1 < y_2 < y_3 < 1\}$$

[Cowan, CCA '01, TRA '02]

Buehgler arm servoing

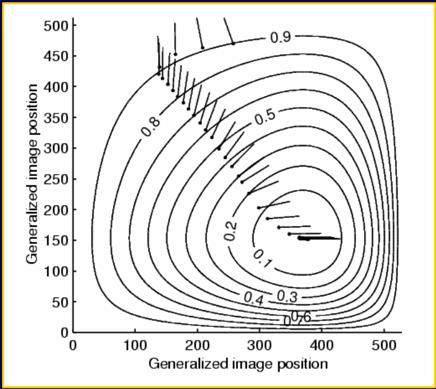
3DOF "juggling" robot adapted for visual servoing

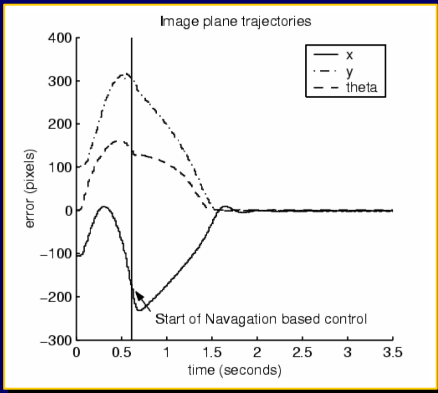


[Rizzi, Whitcomb, Koditschek '92]

Buehgler: typical trials

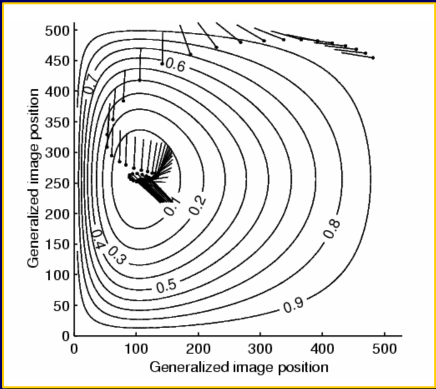
"Critically damped" gains

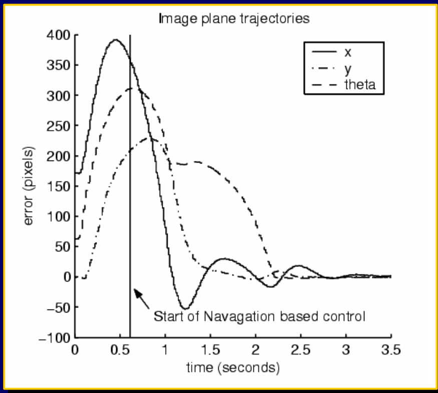




Buehgler: typical trials

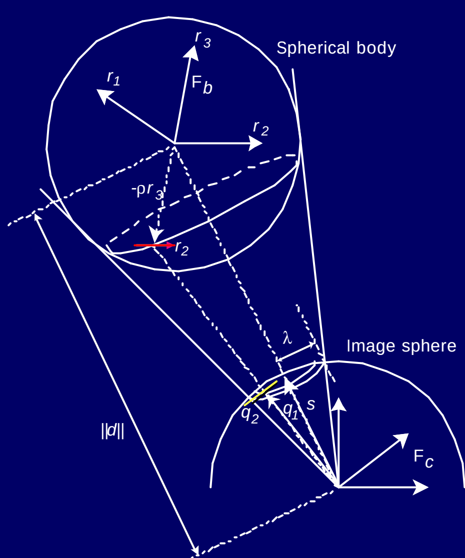
"Under-damped" gains





[Cowan and Chang, CPRA '02]

Generalization for a 6DOF body



$$H = \begin{bmatrix} R & \mathbf{d} \\ 0 & 1 \end{bmatrix} \in V \subset SE(3)$$

$$\boxed{y = c(H)}$$

$$y = (Q = [q_1, q_2, q_3], l, s) \in I$$

$$\subset SO(3) \times R \times S^2$$

Preliminary Simulations

QuickTime™ and a decompressor are needed to see this picture. QuickTime™ and a decompressor are needed to see this picture.

[Cowan et. al, CDC ‘00, TRA ‘02]

6DOF Visual Servoing

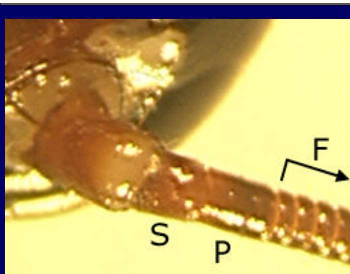
Visual Servoing on RHex

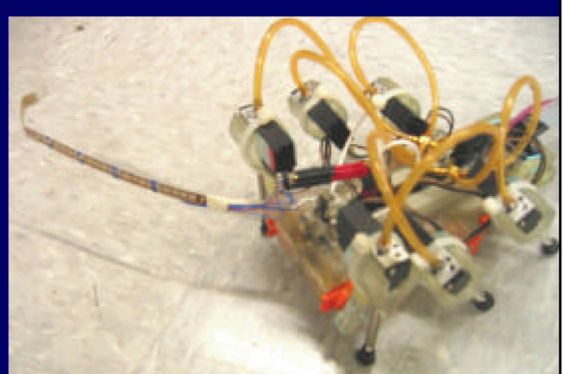
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

[Lopes, Koditschek et al.]

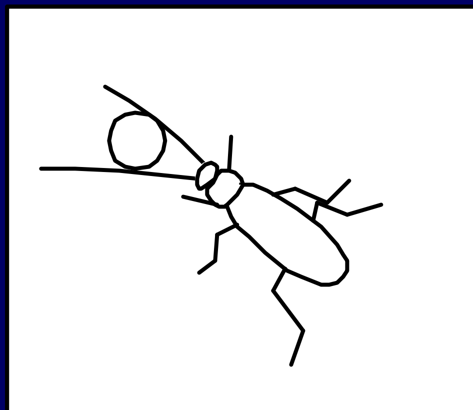
Another sensor-based coordinate system: A Bio-inspired Antenna

[Cowan, et. al., *in review*]





Tactile Orientation



Tactile Orientation: background

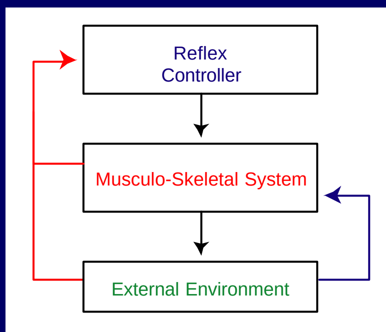
- Cockroach antenna mechano-receptors appear to encode *distance* from and *angle* to an object Okada and Toh [2001]
- A *feedback control hypothesis* has not been formulated for this behavior

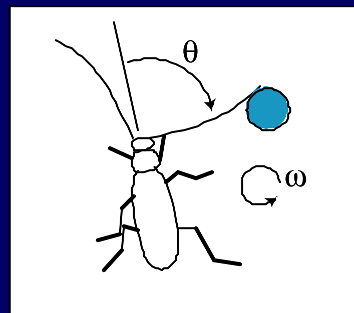
[Okada and Toh 2001]

Tactile Orientation: hypothesis

Hypothesis:

Behavior may be modeled as a 'first-order' reflex

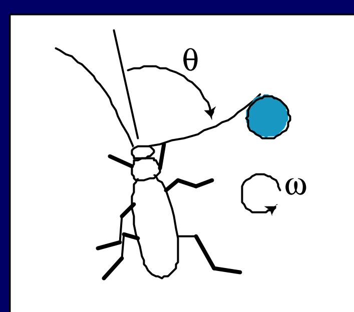




$$\dot{q} = w$$
$$w = -Kq$$

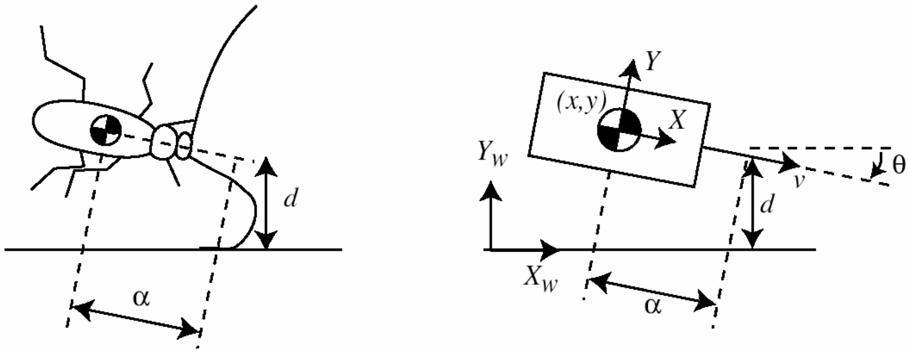
Tactile Orientation: testing

- Data in the literature [Okada and Toh 2001] is consistent with this hypothesis
- I am now designing a set of experiments to attempt to refute this hypothesis
- Anecdotal data seems consistent -- *stay tuned* for more rigorous experiments!



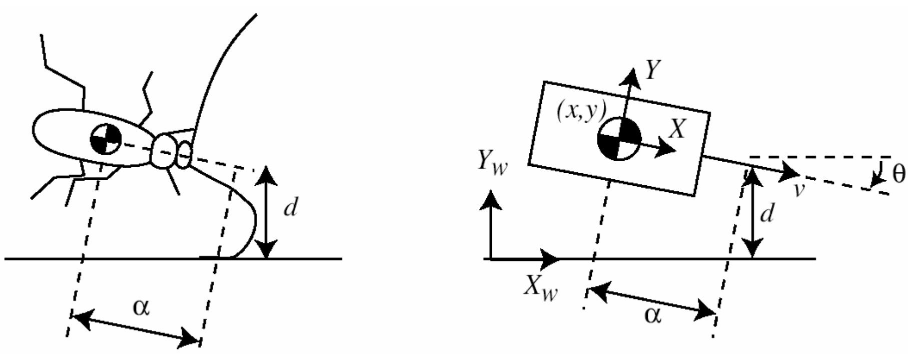
$$\dot{q} = w$$
$$w = -Kq$$

Dynamical wall following



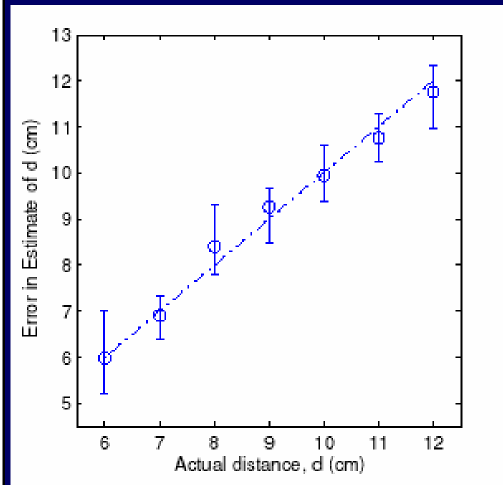
$$G(s) = \frac{D(s)}{U(s)} = \overbrace{\frac{\alpha s + v}{s}}^{\text{sensing}} \cdot \overbrace{\frac{1}{ms^2 + bs}}^{\text{mechanics}}$$

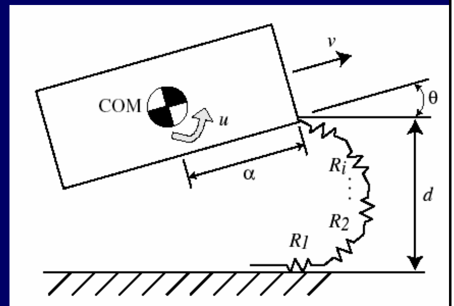
Dimensionless Dynamics

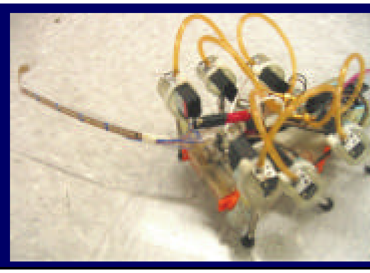


$$\widetilde{G}(w) = \frac{w+1}{w^2(\tau w + 1)} \qquad \tau = \frac{mv}{b\alpha}$$

Design:
a novel “distance & angle” sensor







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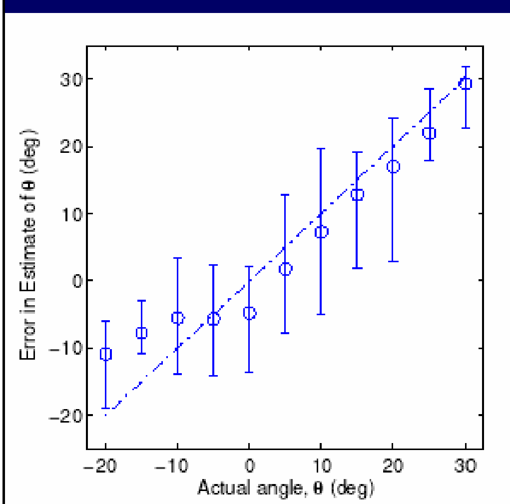
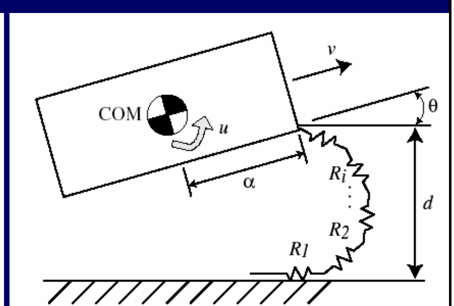
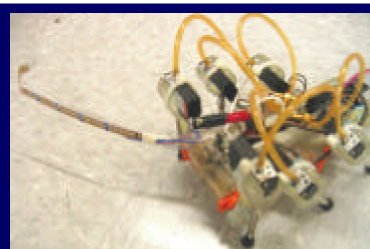






Robotic Integration: wall following

K_P

QuickTime™ and a MPEG-4 Video decompressor are needed to see this picture. QuickTime™ and a MPEG-4 Video decompressor are needed to see this picture.

Result:

Tactile flow

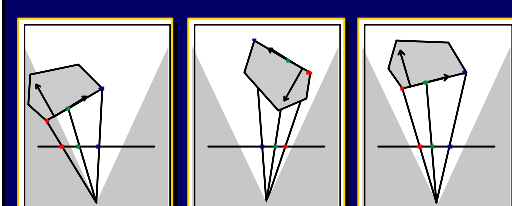
is critical

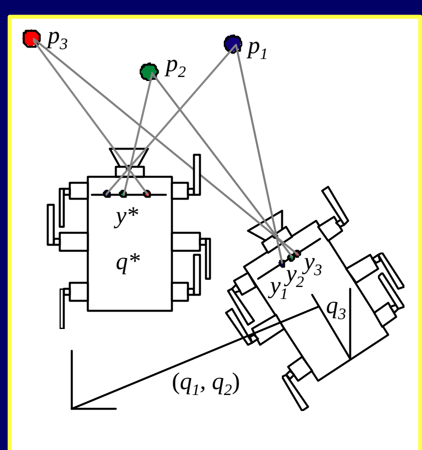
QuickTime™ and a MPEG-4 Video decomp

K_D

Summary

- Vision-based control
  - diffeomorphism from *visible set* to *image space*
  - *visibility* is naturally encoded in image, but not in task space
  - Navigation Functions ensure *global*, *dynamical* convergence while avoiding obstacles





Acknowledgements

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  - Robert Full and the PolyPEDAL Lab
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  - Emily Ma, Mark Cutkosky and the Biomimetics Lab
  - Dong Eui Chang
  - Domenico Prattichizzo and Jacopo Piazzi

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