



Robotics 2

Visual servoing

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Visual servoing

- objective
 - use information acquired by **vision sensors** (cameras) for **feedback control** of the pose/motion of a robot (or of parts of it)
- + data acquisition ~ human eye, with very large information content in the acquired images
- difficult to extract essential data, nonlinear perspective transformations, high sensitivity to ambient conditions (lightening), noise



Some applications

automatic navigation of robotic systems (agriculture, automotive)

video



video



surveillance

video



bio-motion synchronization (surgical robotics)

video





Image processing

- **real-time** extraction of characteristic parameters useful for robot motion control
 - **features:** points, area, geometric center, higher-order moments, ...
- low-level processing
 - binarization (threshold on grey levels), equalization (histograms), edge detection, ...
- segmentation
 - based on regions (possibly in binary images)
 - based on contours
- interpretation
 - association of characteristic parameters (e.g., texture)
 - problem of **correspondence** of points/characteristics of objects in different images (stereo or on image flows)

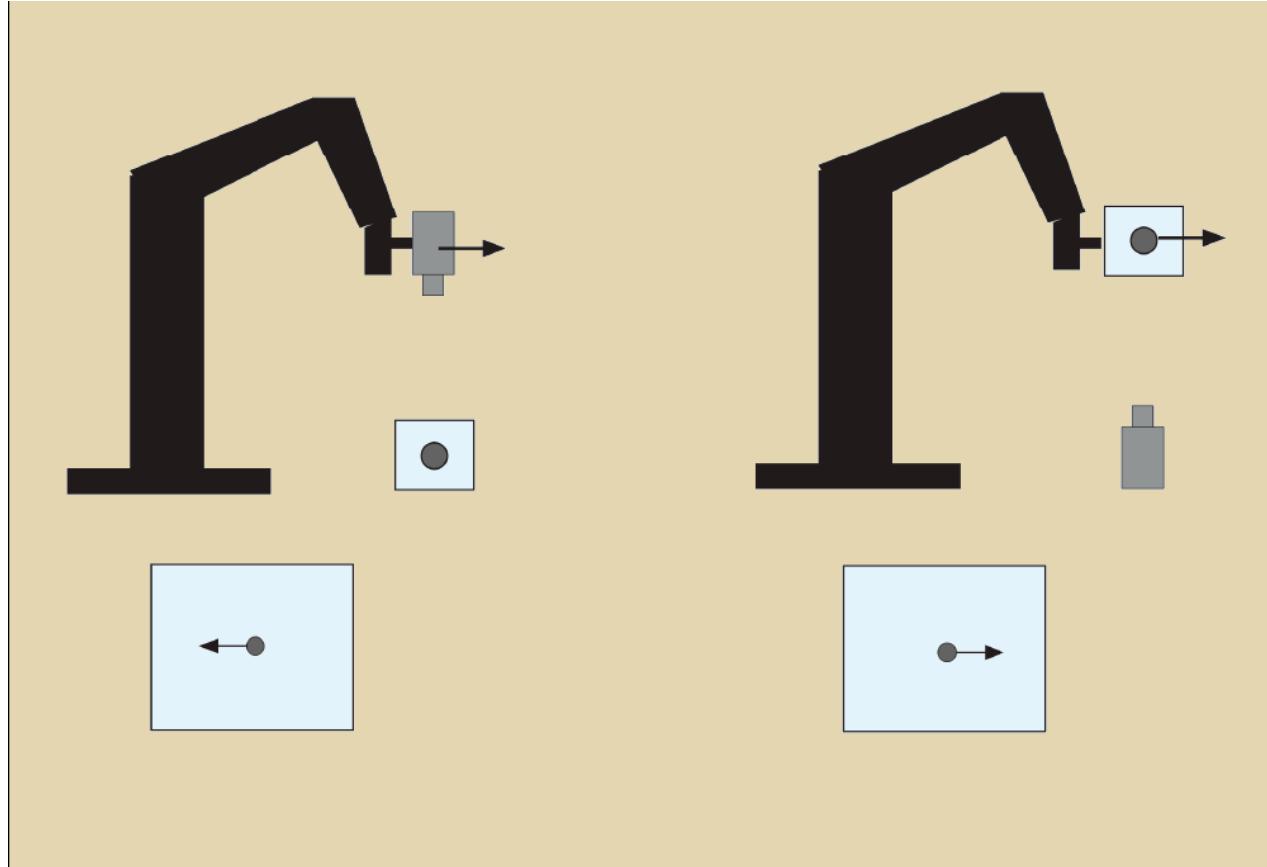


Configuration of a vision system

- one, two, or more cameras
 - grey-level or color
- 3D/stereo vision
 - obtained even with a single (moving) camera, with the object taken from different (known) points of view
- camera positioning
 - fixed (eye-to-hand)
 - mounted on the manipulator (eye-in-hand)
- robotized vision heads
 - motorized (e.g., stereo camera on humanoid head or pan-tilt camera on Magellan mobile robot)



Camera positioning



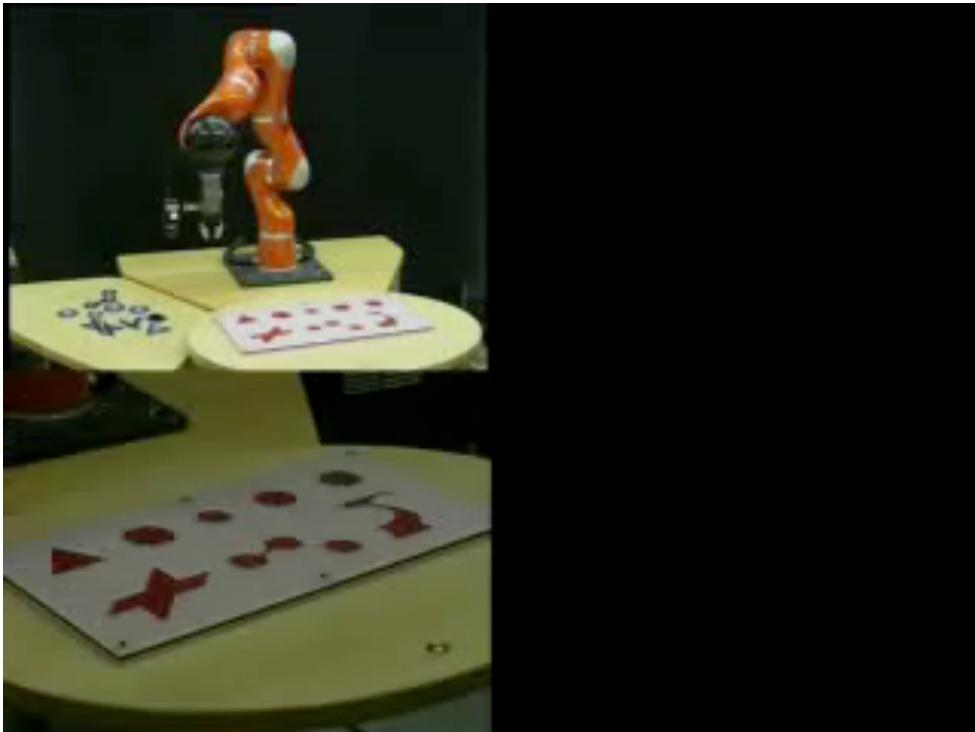
eye-in-hand

eye-to-hand



Vision for assembly

video



video

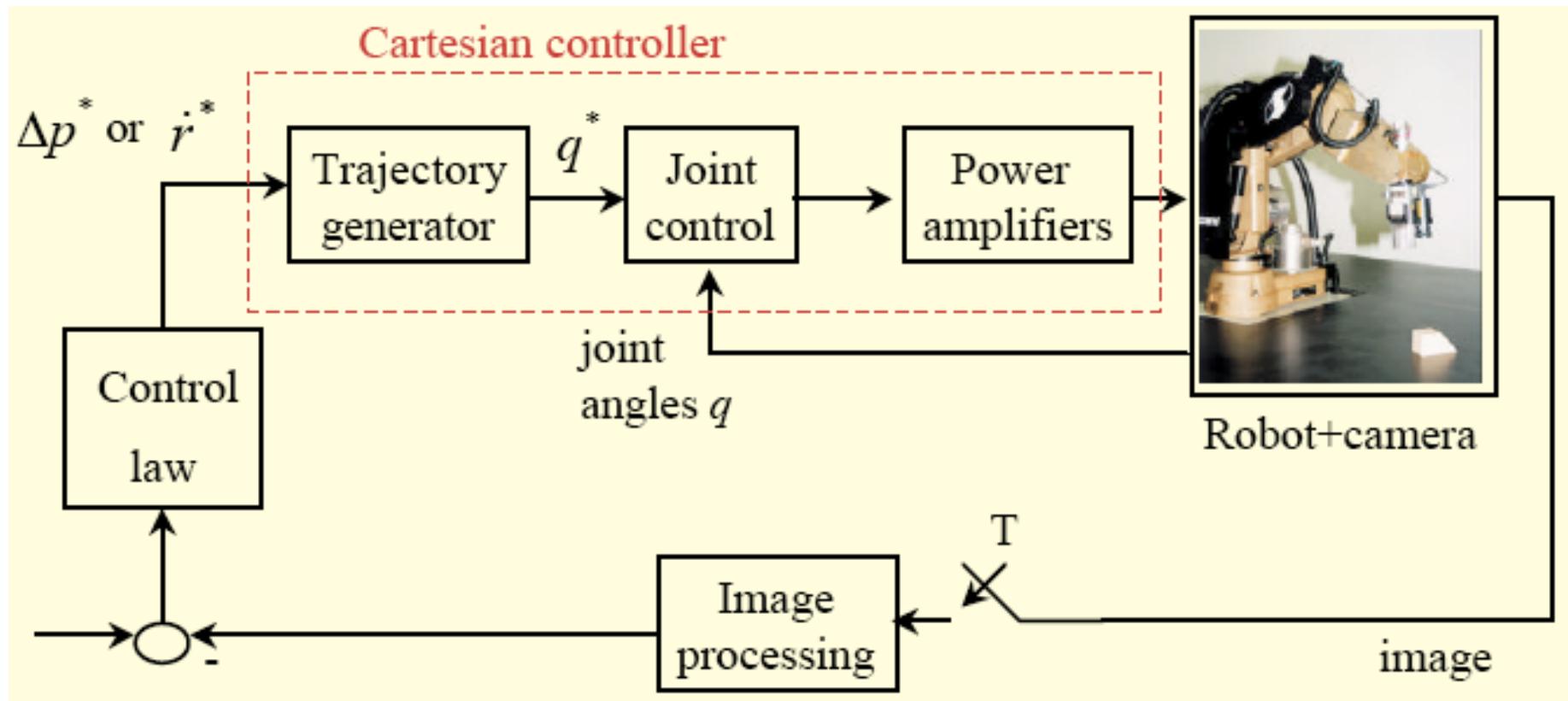


PAPAS-DLR system
(eye-in-hand, **hybrid force-vision**)

robust w.r.t. motion of
target objects



Indirect/external visual servoing

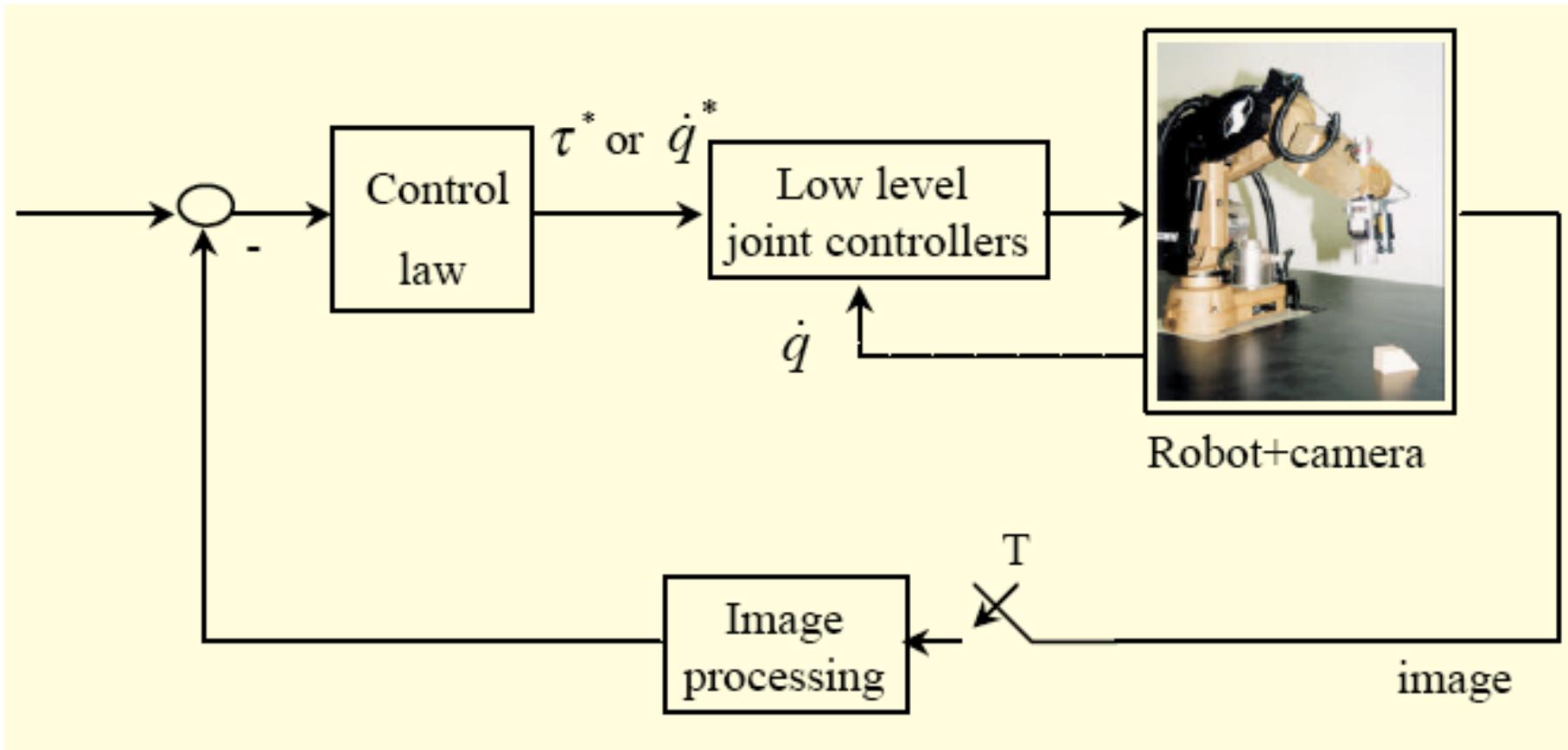


vision system **provides set-point references** to a **Cartesian motion controller**

- “easy” control law (same as without vision)
- appropriate for relatively slow situations (control sampling $f = 1/T < 50\text{Hz}$)



Direct/internal visual servoing



replace Cartesian controller with one based on vision that **directly computes joint reference commands**

- control law is more complex (involves robot kinematics/dynamics)
- preferred for fast situations (control sampling $f = 1/T > 50\text{Hz}$)



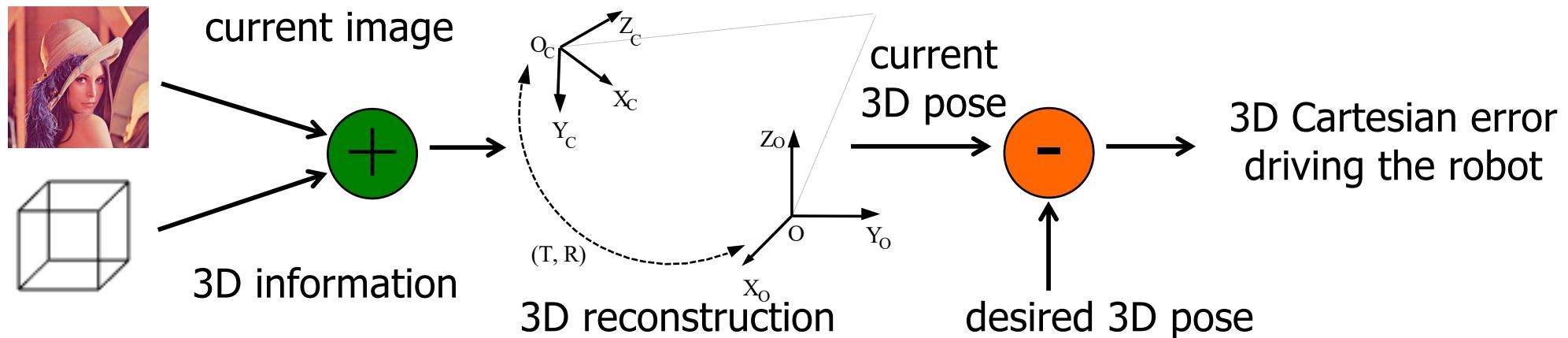
Classification of visual servoing schemes

- position-based visual servoing (**PBVS**)
 - information extracted from images (**features**) is used to reconstruct the **current 3D pose** (pose/orientation) of an object
 - combined with the knowledge of a **desired 3D pose**, we generate a **Cartesian** pose error signal that drives the robot to the goal
- image-based visual servoing (**IBVS**)
 - error is computed directly on the values of the features extracted on the **2D image plane**, **without** going through a 3D reconstruction
 - the robot should move so as to bring the current image features (what it “sees” with the camera) to their desired values
- some mixed schemes are possible (e.g., **2½D methods**)

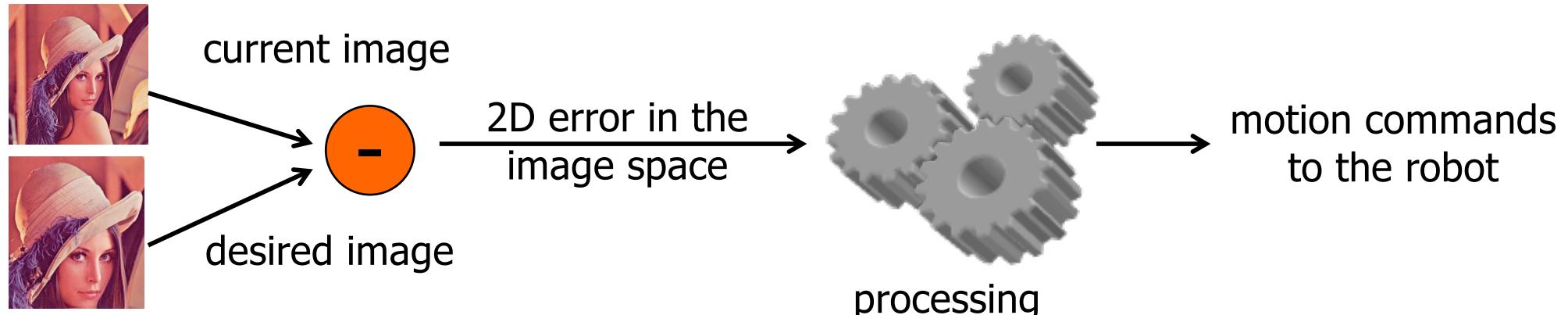


Comparison between the two schemes

- position-based visual servoing (**PBVS**)

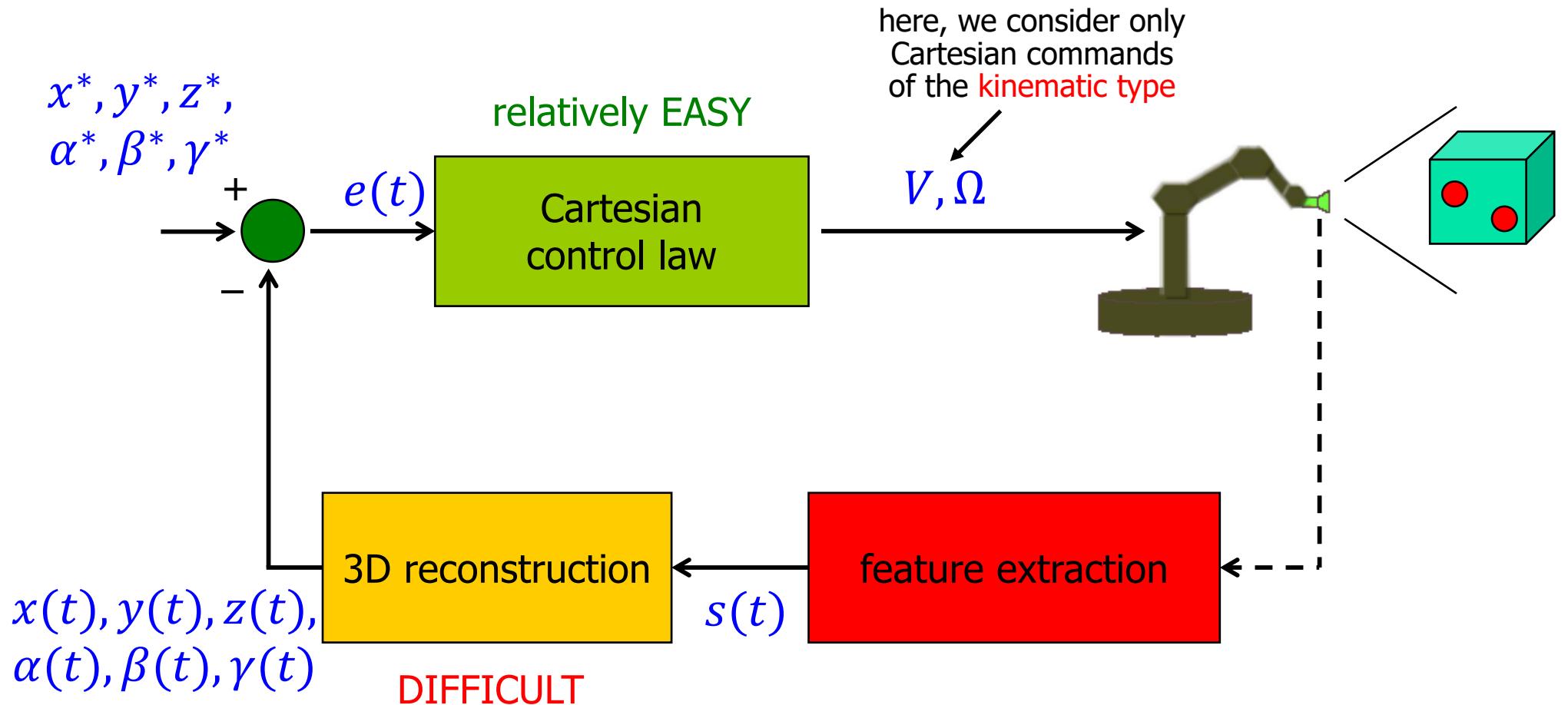


- image-based visual servoing (**IBVS**)





PBVS architecture

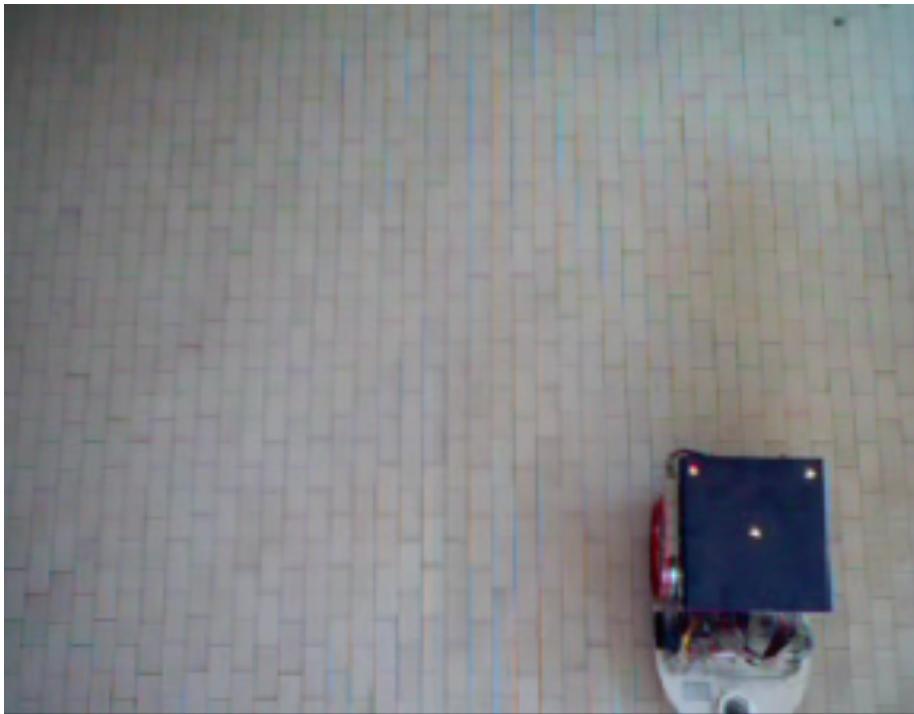


highly sensitive to camera calibration parameters



Examples of PBVS

video



eye-to-“robot” (SuperMario)

position/orientation of the camera
and scene geometry

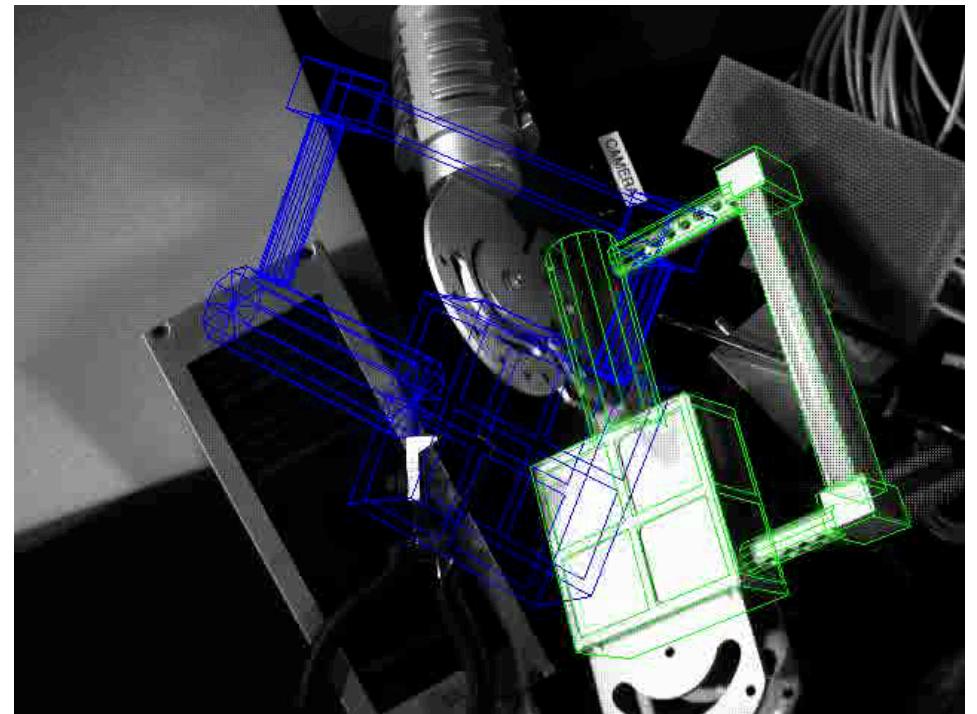


eye-in-hand (Puma robot)

position and orientation of the robot
(with mobile or fixed base)

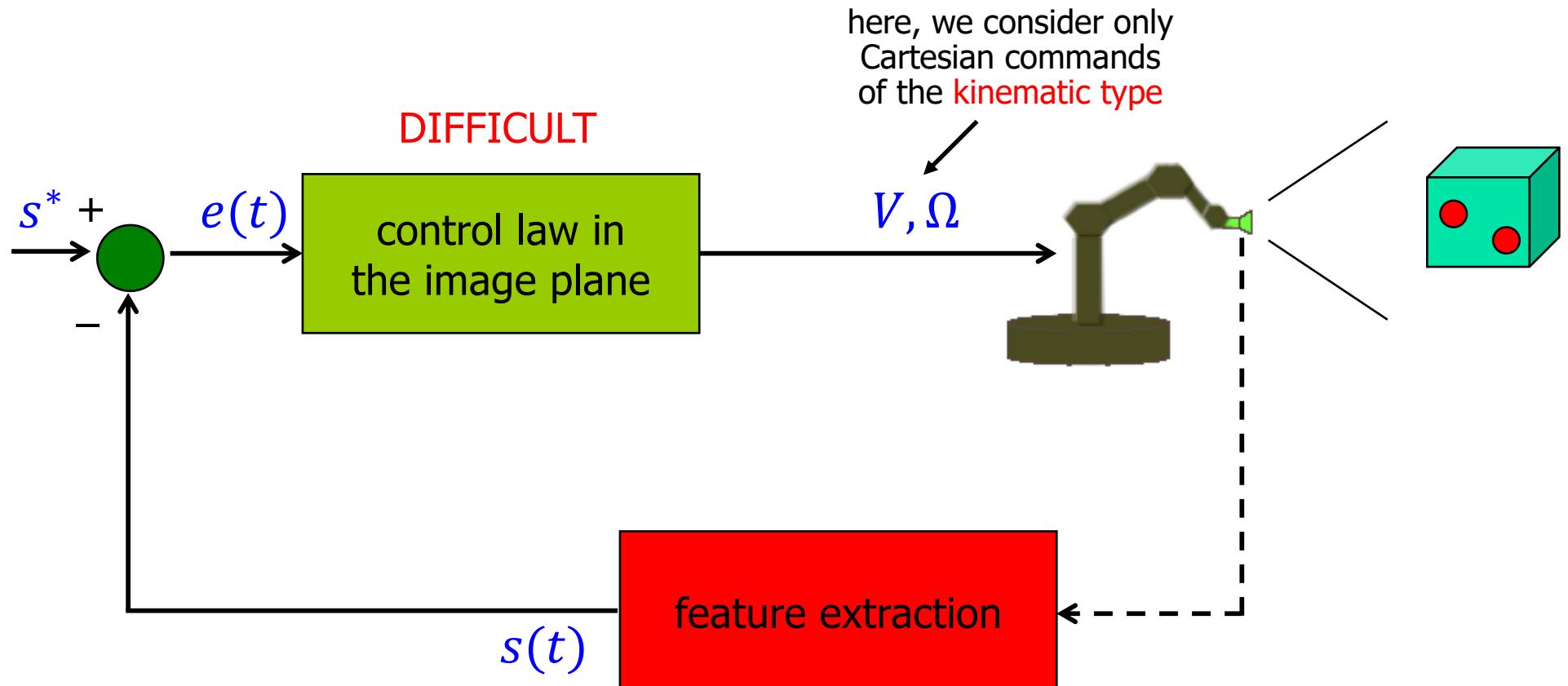
known a priori!

video





IBVS architecture

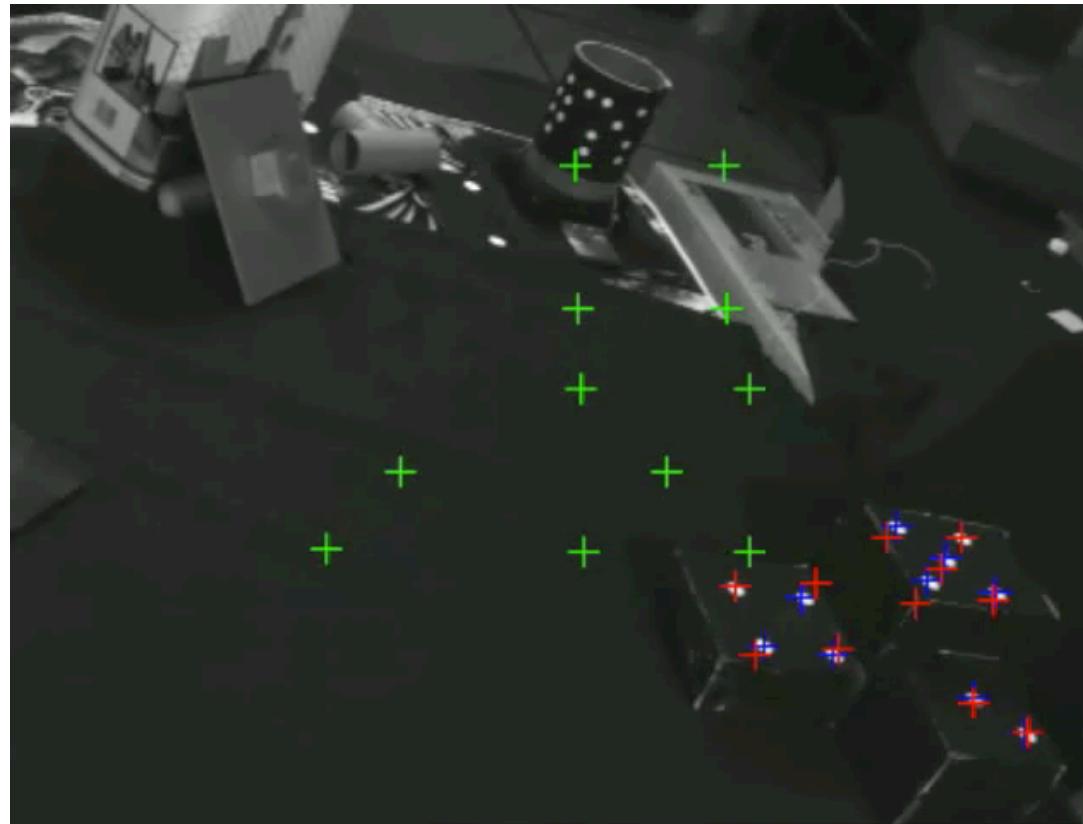


almost insensitive to intrinsic/extrinsic camera calibration parameters



An example of IBVS

here, the features are **points** (selected from the given set, or in suitable combinations)



video

desired feature positions
current feature positions



the error in the image plane (task space!) drives/controls the motion of the robot



PBVS vs IBVS

PBVS = position-based
visual servoing

video



IBVS = image-based
visual servoing

video



F. Chaumette, INRIA Rennes

reconstructing the instantaneous
(relative) 3D pose of the object

using (four) point features
extracted from the 2D image

...and intermediate 2½-D visual servoing...

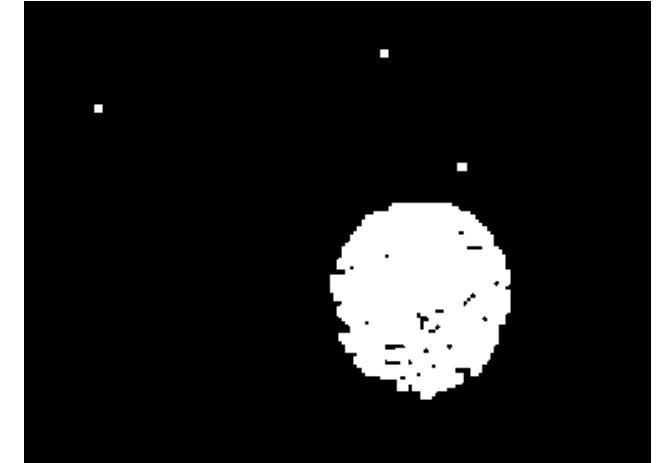
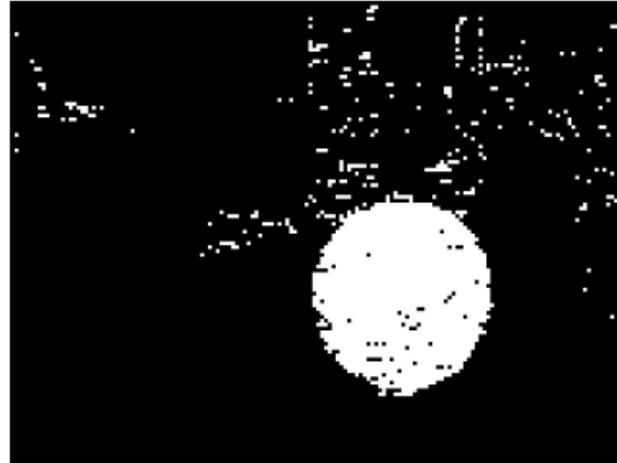


Steps in an IBVS scheme

- **image acquisition**
 - frame rate, delay, noise, ...
- **feature extraction**
 - with image processing techniques (it could be a difficult and time consuming step!)
- **comparison with “desired” feature values**
 - definition of an **error** signal in the **image plane**
- **generation of motion of the camera/robot**
 - perspective transformations
 - differential kinematics of the manipulator
 - control laws of **kinematic** (most often) or **dynamic** type (e.g., PD + gravity cancelation --- **see reference textbook**)



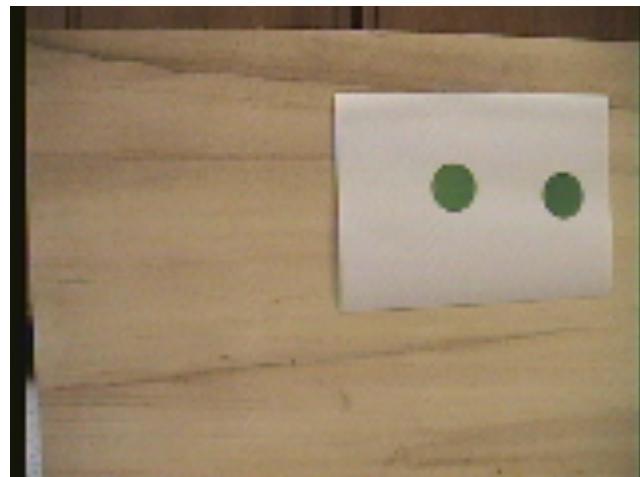
Image processing techniques



binarization in **RGB** space



erosion and dilation



binarization in **HSV** space



dilation

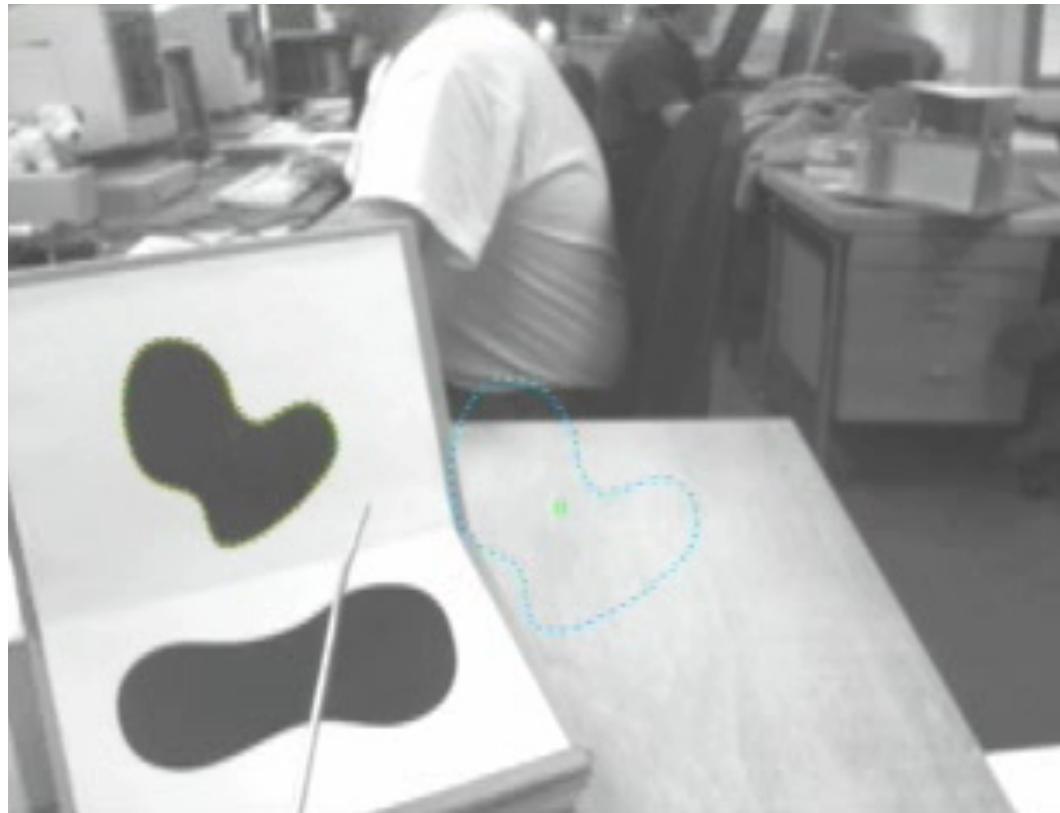


What is a feature?

- **image feature**: any interesting **characteristic** or **geometric structure** extracted from the image/scene
 - points
 - lines
 - ellipses (or any other 2D contour)
- **feature parameter(s)**: any **numerical quantity** associated to the selected feature in the image plane
 - coordinates of a point
 - angular coefficient and offset of a line
 - center and radius of a circle
 - area and center of a 2D contour
 - generalized **moments** of an object in the image
 - can also be defined so as to be scale- and rotation-invariant



Example of IBVS using moments



video

- avoids the problem of “finding **correspondences**” between points
- however, it is not easy to control the motion of all **6 dofs of the camera** when using only moments as features

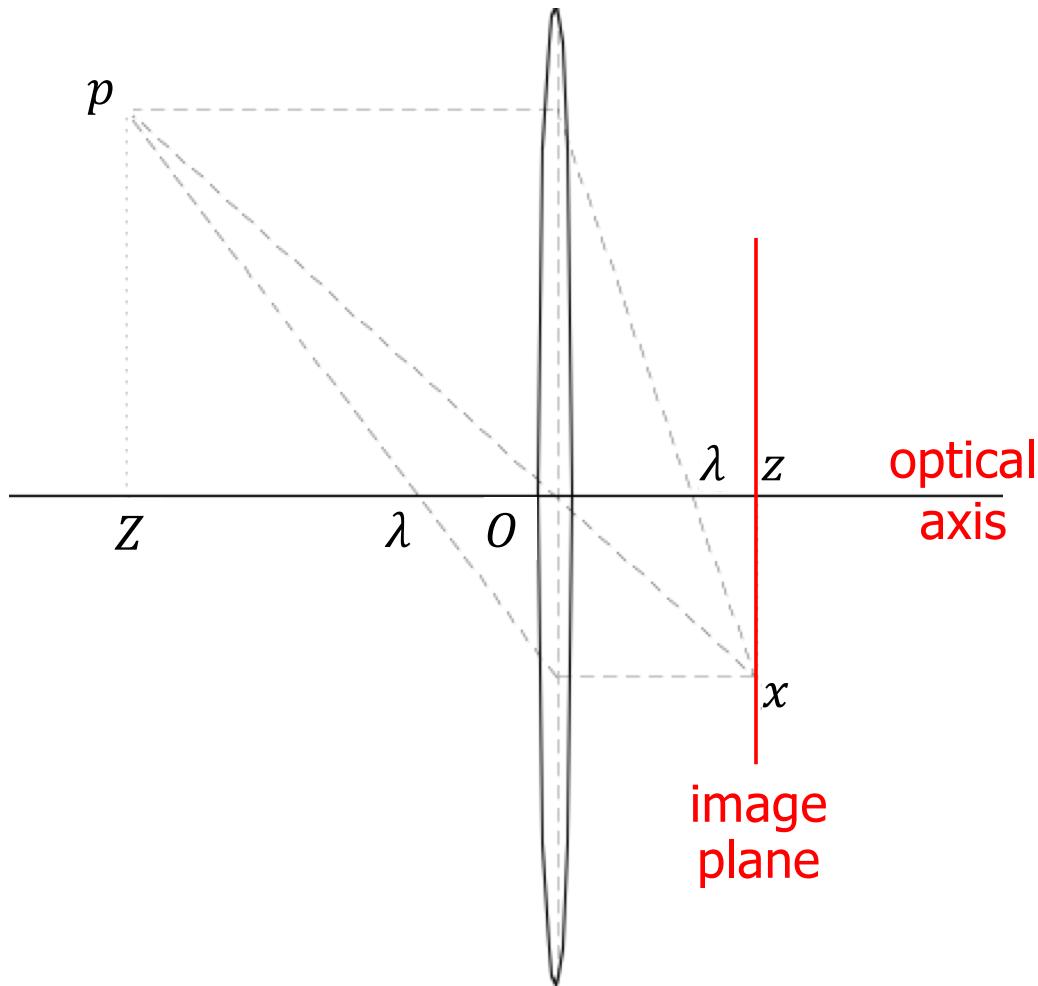


Camera model

- set of **lenses** to focus the incoming light
 - (converging) thin lenses
 - pinhole approximation
 - catadioptric lens or systems (combined with mirrors)
- matrix of light sensitive elements (pixels in **image plane**), possibly selective to **RGB** colors ~ human eye
- **frame grabber** “takes shots”: an electronic device that captures individual, digital still frames as output from an analog video signal or a digital video stream
 - board + software on PC
 - **frame rate** = output frequency of new digital frames
 - it is useful to randomly access a subset (area) of pixels



Thin lens camera model



- geometric/projection optics
- rays parallel to the optical axis are deflected through a point at distance λ (**focal length**)
- rays passing through the optical center O are **not** deflected

fundamental equation
of a thin lens

$$\frac{1}{Z} + \frac{1}{z} = \frac{1}{\lambda}$$

} dioptic
(optical)
power

proof? left as exercise ...



Pinhole camera model

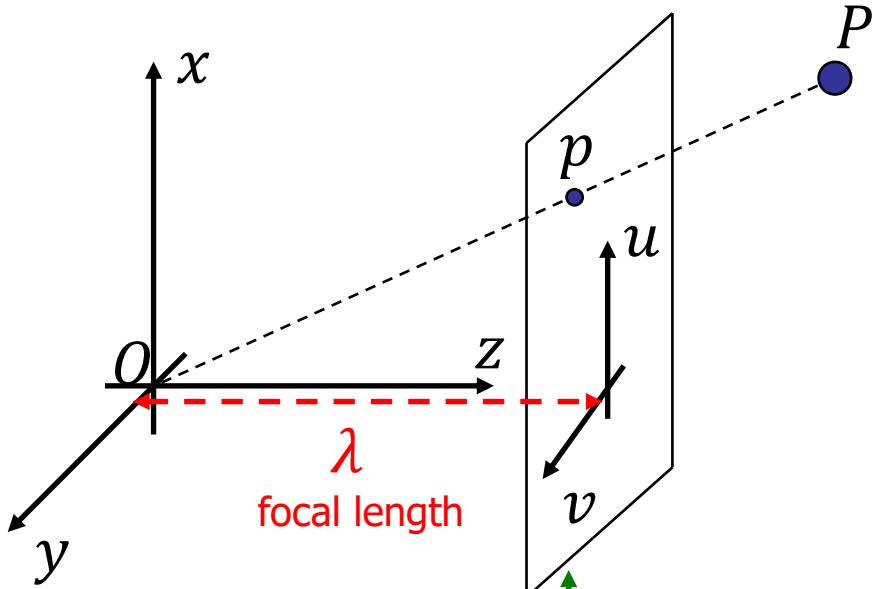


image plane with an array of light sensitive elements
 (actually located symmetrically to the optical center O , but this model avoids a change of signs...)

- when thin lens wideness is neglected
- all rays pass through optical center
- from the relations on similar triangles one gets the **perspective equations**

$$u = \lambda \frac{X}{Z} \quad v = \lambda \frac{Y}{Z}$$

to obtain these from discrete pixel values, an **offset** and a **scaling factor** should be included in each direction

sometimes **normalized** values (u', v') are used
 (dividing by the focal length)

with

$$P = (X, Y, Z)$$

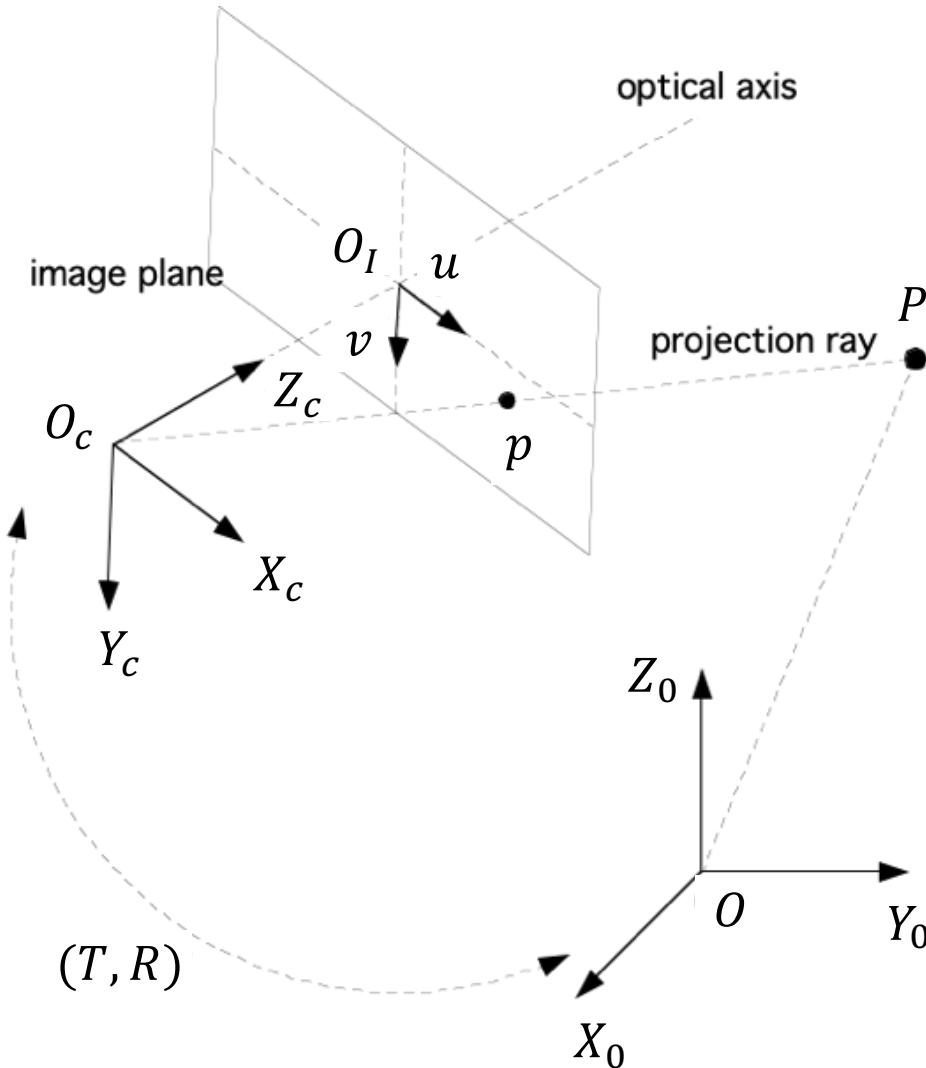
Cartesian point
 (in camera frame)

$$p = (u, v, \lambda)$$

representative point
 on the image plane



Reference frames of interest



- **absolute reference frame**
 $\mathcal{F}_0: \{O, \vec{X}_0, \vec{Y}_0, \vec{Z}_0\}$
- **camera reference frame**
 $\mathcal{F}_c: \{O_c, \vec{X}_c, \vec{Y}_c, \vec{Z}_c\}$
- **image plane reference frame**
 $\mathcal{F}_I: \{O_I, \vec{u}, \vec{v}\}$
- **position/orientation of \mathcal{F}_c w.r.t. \mathcal{F}_0**
 (T, R)
 (translation, rotation)



Interaction matrix

- given a set of feature(s) parameters $f = [f_1 \quad \cdots \quad f_k]^T \in \mathbb{R}^k$
- we look for the **(kinematic) differential relation** between **motion imposed to the camera** and **motion of features** on the image plane

$$\dot{f} = J(\cdot) \begin{bmatrix} V \\ \Omega \end{bmatrix}$$

- $(V, \Omega) \in \mathbb{R}^6$ is the camera linear/angular velocity, a vector expressed in \mathcal{F}_c
- $J(\cdot)$ is a $k \times 6$ matrix, known as **interaction matrix**
- in the following, we consider mainly **point features**
 - other instances (areas, lines, ...) can be treated as extensions of the presented analysis



Computing the interaction matrix point feature, pinhole model

- from the perspective equations $u = \lambda \frac{X}{Z}$, $v = \lambda \frac{Y}{Z}$, we have

$$\begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} \frac{\lambda}{z} & 0 & -\frac{u}{z} \\ 0 & \frac{\lambda}{z} & -\frac{v}{z} \end{bmatrix} \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = J_1(u, v, \lambda) \begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix}$$

- the velocity $(\dot{X}, \dot{Y}, \dot{Z})$ of a point P in frame \mathcal{F}_c is **actually due to** the roto-translation (V, Ω) of the camera (P is assumed fixed in \mathcal{F}_0)
- kinematic relation between $(\dot{X}, \dot{Y}, \dot{Z})$ and (V, Ω)

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = -V - \Omega \times \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Note: ALL quantities are expressed in the camera frame \mathcal{F}_c
without explicit indication of subscripts



Computing the interaction matrix (cont)

point feature, pinhole model

- the last equation can be expressed in matrix form

$$\begin{bmatrix} \dot{X} \\ \dot{Y} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 & 0 & -Z & Y \\ 0 & -1 & 0 & Z & 0 & -X \\ 0 & 0 & -1 & -Y & X & 0 \end{bmatrix} \begin{bmatrix} V \\ \Omega \end{bmatrix} = J_2(X, Y, Z) \begin{bmatrix} V \\ \Omega \end{bmatrix}$$

- combining things, the **interaction matrix** for a **point feature** is

$$\begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = J_1 J_2 \begin{bmatrix} V \\ \Omega \end{bmatrix} = \begin{bmatrix} -\frac{\lambda}{Z} & 0 & \frac{u}{Z} & \frac{uv}{\lambda} & -\left(\lambda + \frac{u^2}{\lambda}\right) & v \\ 0 & -\frac{\lambda}{Z} & \frac{v}{Z} & \lambda + \frac{v^2}{\lambda} & -\frac{uv}{\lambda} & -u \end{bmatrix} \begin{bmatrix} V \\ \Omega \end{bmatrix}$$

$$= J_p(u, v, Z) \begin{bmatrix} V \\ \Omega \end{bmatrix}$$



p = point (feature)

here, λ is assumed to be known



Comments

- the **interaction matrix** in the map

$$\begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = J_p(u, v, Z) \begin{bmatrix} V \\ \Omega \end{bmatrix}$$

- depends on the actual value of the **feature** and on its **depth Z**
- since $\dim \ker J_p = 4$, there exist ∞^4 motions of the camera that are unobservable (for this feature) on the image
 - for instance, a translation along the projection ray
- when **more point features** are considered, the associated interaction matrices are stacked one on top of the other
 - p point features: the interaction matrix is $k \times 6$, with $k = 2p$



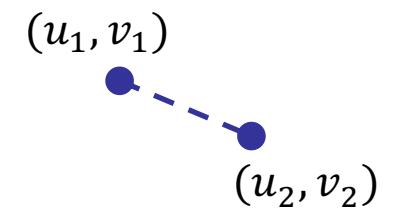
Other examples of interaction matrices

- distance between two point features

$$d = \sqrt{(u_1 - u_2)^2 + (v_1 - v_2)^2}$$

$$\dot{d} = \frac{1}{d} [u_1 - u_2 \quad v_1 - v_2 \quad u_2 - u_1 \quad v_2 - v_1] \begin{bmatrix} \dot{u}_1 \\ \dot{v}_1 \\ \dot{u}_2 \\ \dot{v}_2 \end{bmatrix}$$

$$= J_p(u_1, u_2, v_1, v_2) \begin{bmatrix} J_{p1}(u_1, v_1, Z_1) \\ J_{p2}(u_2, v_2, Z_2) \end{bmatrix} \begin{bmatrix} V \\ \Omega \end{bmatrix}$$



- image moments

$$m_{ij} = \iint_{\mathcal{R}(t)} x^i y^j dx dy$$

$\mathcal{R}(t)$ region of the image plane
occupied by the object

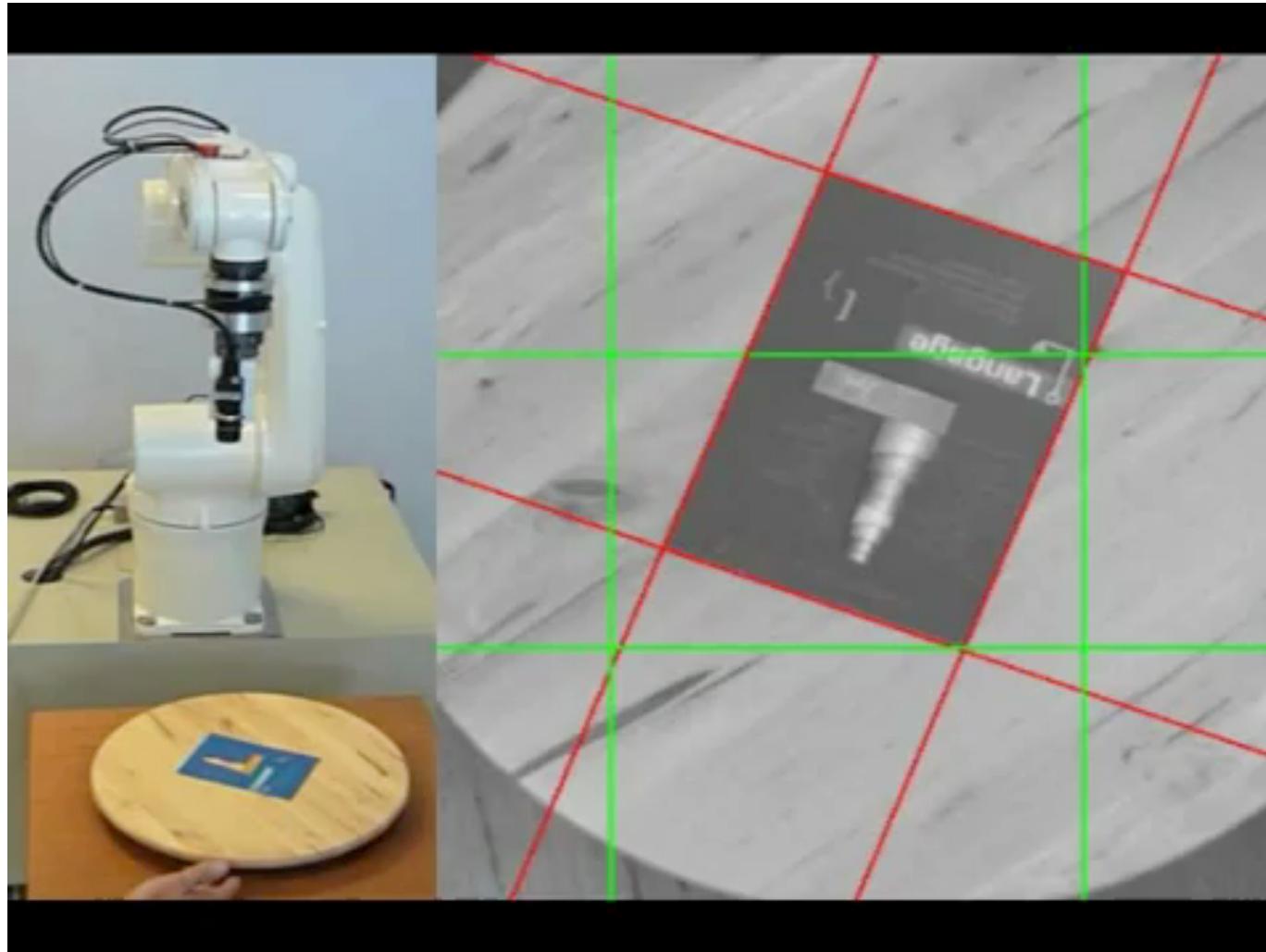
- useful for representing also qualitative geometric information ([area](#), [center](#), [orientation of an approximating ellipse](#), ...)
- by using Green formulas and the interaction matrix of a generic point feature

$$\rightarrow \dot{m}_{ij} = L_{ij} \begin{bmatrix} V \\ \Omega \end{bmatrix}$$

(see F. Chaumette: "Image moments:
A general and useful set of features for visual servoing",
IEEE Trans. on Robotics, August 2004)



IBVS with straight lines as features



F. Chaumette, INRIA Rennes



Robot differential kinematics

- **eye-in-hand** case: camera is mounted on the **end-effector** of a manipulator arm (with fixed base or on a wheeled mobile base)
 - the motion (V, Ω) to be imposed to the camera coincides with the desired **end-effector linear/angular velocity** and is realized by choosing the manipulator **joint velocity** (or, more in general, the feasible **velocity commands** of a **mobile** manipulator)

$$\begin{bmatrix} V \\ \Omega \end{bmatrix} = J_m(q)\dot{q} = J_m(q)u$$

velocity
control
input

↑
Geometric Jacobian
of a manipulator

↑
... or the NMM Jacobian
of a mobile manipulator

for consistency with the previous interaction matrix, these Jacobians must be expressed in the camera frame \mathcal{F}_c

with $q \in \mathbb{R}^n$ being the robot configuration variables

- in general, an hand-eye calibration is needed for this Jacobian



Image Jacobian

- combining the step involved in the passage from the **velocity of point features** on the image plane to the **joint velocity/feasible velocity commands of the robot**, we finally obtain

$$\dot{f} = J_p(f, Z)J_m(q)u = J(f, Z, q)u$$

- matrix $J(f, Z, q)$ is called the **Image Jacobian** and plays the same role of a classical robot Jacobian
- we can thus apply one of the many standard kinematic (or even dynamics-based) control techniques for robot motion
- the (controlled) **output** is given by the vector of features in the image plane (the **task space!**)
- the **error** driving the control law is defined in this task space



Kinematic control for IBVS

- defining the error vector as $e = f_d - f$, the general choice

$$u = J^{\#}(\dot{f}_d + ke) + (I - J^{\#}J)u_0$$

minimum norm solution

term in $\ker J$ does not “move” the features

will **exponentially stabilize** the task error to zero (up to singularities, limit joint range/field of view, features exiting the image plane, ...)

- in the redundant case, vector u_0 (projected in the image Jacobian null space) can be used for optimizing behavior/criteria
- the error feedback signal **depends only on feature values**
- there is still a dependence of J on the **depths** Z of the features
 - use the constant and “known” values at the final **desired pose**
 - or, **estimate on line** their current values using a dynamic observer

$$J(f, Z^*, q)$$



Example with NMM

- mobile base (unicycle) + 3R manipulator
- eye-in-hand configuration
- 5 commands
 - linear and angular velocity of mobile base
 - velocities of the three manipulator joints
- task specified by 2 point features → 4 output variables



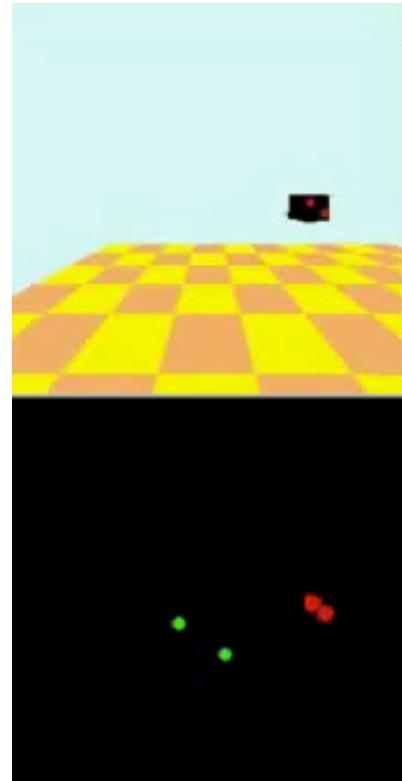
$$f = [f_{u1} \quad f_{v1} \quad f_{u2} \quad f_{v2}]^T$$

- $5 - 4 = 1$ degree of redundancy (w.r.t. the task)

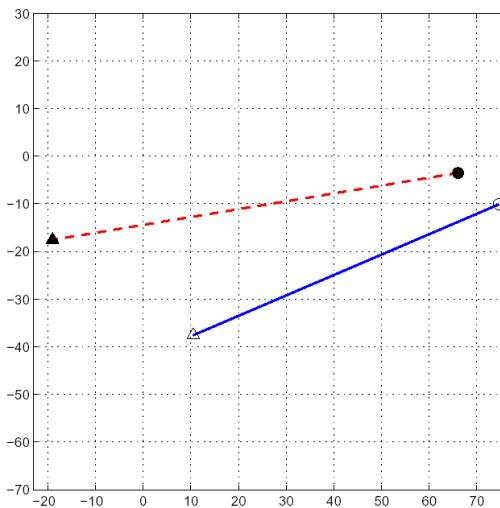


Simulation

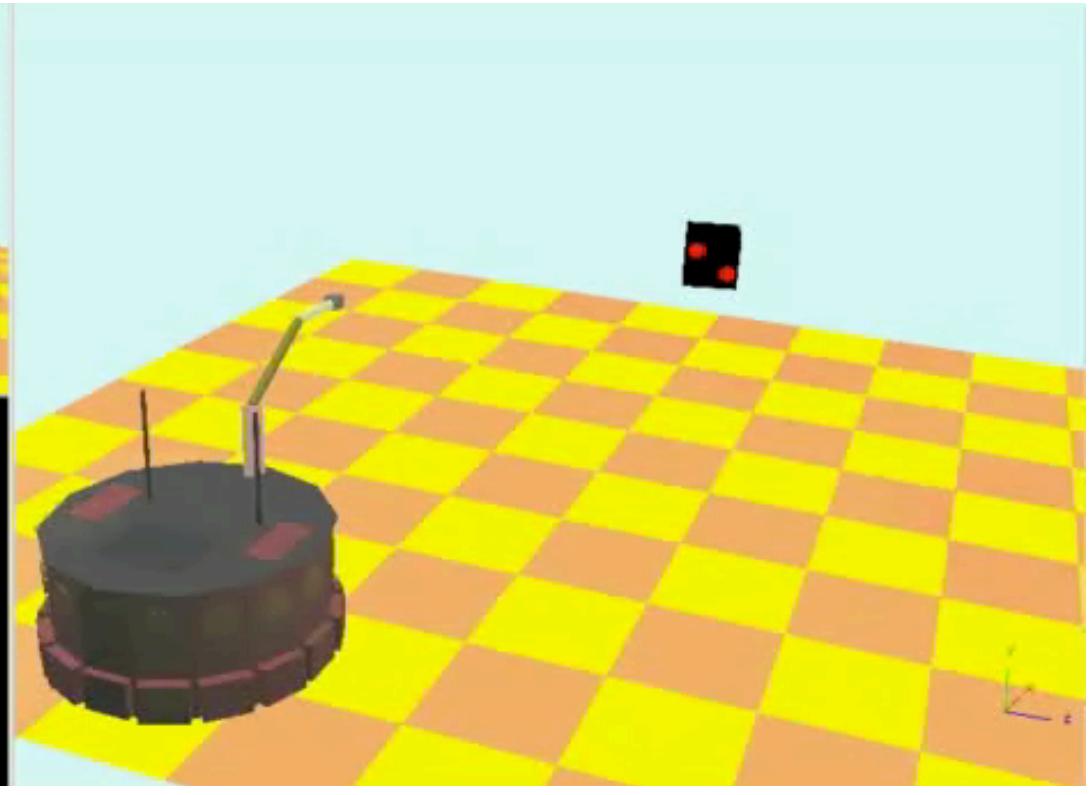
view from
camera



processed
image



behavior of
the 2 features



video

- simulation in Webots
- current value of Z is supposed to be known
- diagonal task gain matrix k (decoupling!)
- “linear paths” of features motion on the image plane



IBVS control with Task Sequencing

- approach: **regulate only one (some) feature** at the time, while keeping “**fixed**” the others by **unobservable motions** in the image plane

- Image Jacobians of single point features (e.g., $p = 2$)

$$\dot{f}_1 = J_1 u, \quad \dot{f}_2 = J_2 u$$

- the first feature f_1 is regulated during a first phase by using

$$u = J_1^\# k_1 e_1 + (I - J_1^\# J_1) u_0$$

- feature f_2 is then regulated by a command in the null-space of the first task

$$u = (I - J_1^\# J_1) J_2^T k_2 e_2$$

- in the first phase there are **two (more) degrees of redundancy** w.r.t. the “**complete**” case, which can be used, e.g., for improving robot alignment to the target

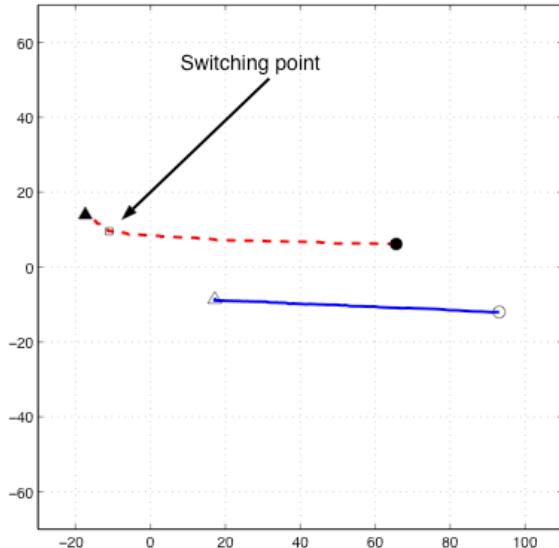
- if the complete case is **not** redundant: singularities are typically met without Task Sequencing, but possibly prevented with TS ...



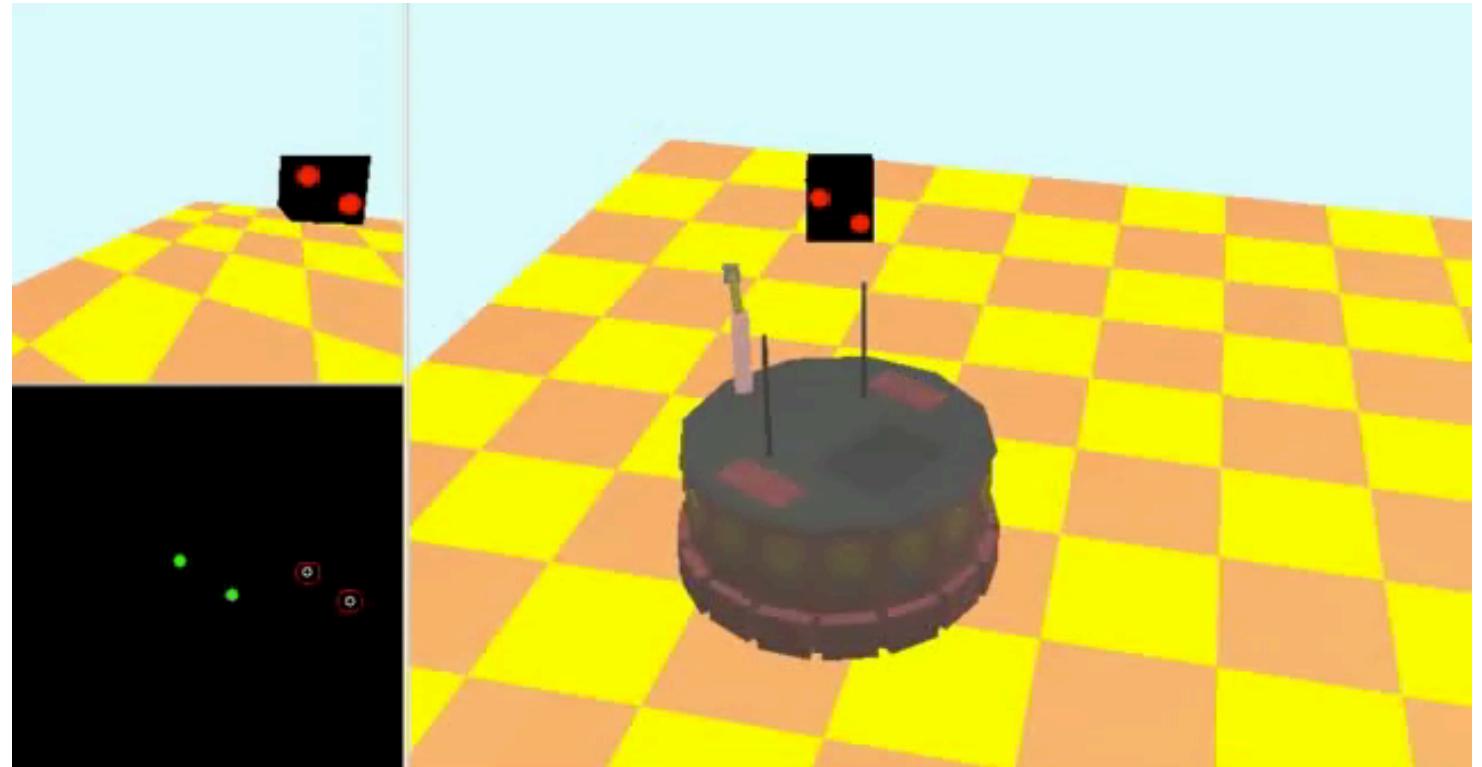
Simulation with TS scheme

mobile base (unicycle) + polar 2R arm: Image Jacobian is square (4×4)

point feature 1
(regulated in
first phase)
point feature 2
(in second phase)



behavior of
the 2 features



video

- simulation in Webots
- current value of Z is supposed to be known



Experiments

Magellan (unicycle) + pan-tilt camera (same mobility of a polar 2R robot)



Video attachment to ICRA'08 paper

Visual Servoing with Exploitation of Redundancy:
An Experimental Study

A. De Luca

M. Ferri

G. Oriolo

P. Robuffo Giordano

Dipartimento di Informatica e Sistemistica
Università di Roma "La Sapienza"

video

- comparison between **Task Priority (TP)** and **Task Sequencing (TS)** schemes
- both can handle singularities (of Image Jacobian) that are possibly encountered
- camera frame rate = 7 Hz



In many practical cases...

- the uncertainty in a number of relevant data may be large
 - focal length λ (**intrinsic** camera parameters)
 - **hand-eye calibration** (**extrinsic** camera parameters)
 - **depth** Z of point features
 -
- one can only compute an **approximation** of the Image Jacobian (both in its **interaction matrix** part, as well as in the **robot Jacobian** part)
- in the closed loop, error dynamics on features becomes
$$\dot{e} = -J \hat{J}^{\#} K e$$
 - **ideal** case: $J J^{\#} = I$ **real** case: $J \hat{J}^{\#} \neq I$
- it is possible to show that a **sufficient condition** for **local** convergence of the error to zero is

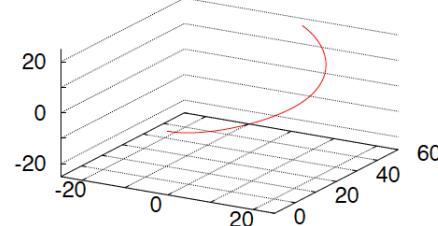
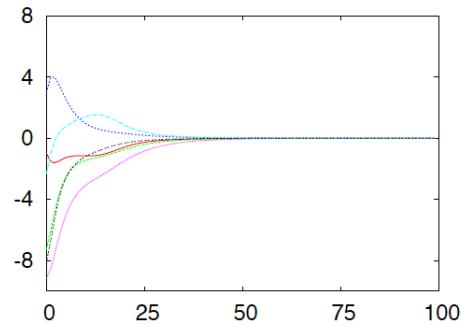
$$J \hat{J}^{\#} > 0$$



Approximate Image Jacobian

- use a constant Image Jacobian $\hat{J}(Z^*)$ that is computed at the desired target s^* (with a known, fixed depth Z^*)

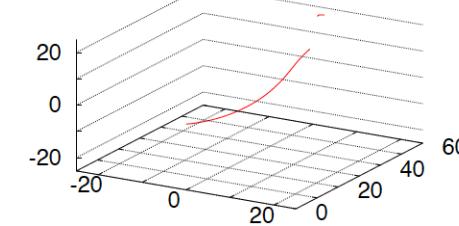
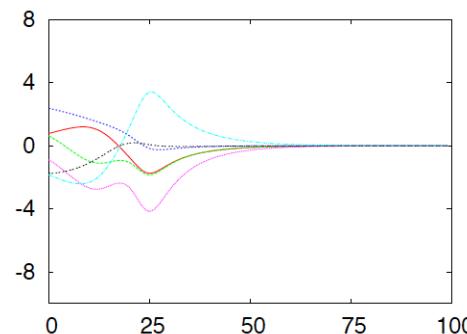
$$\dot{q} = J^\#(Z)Ke$$



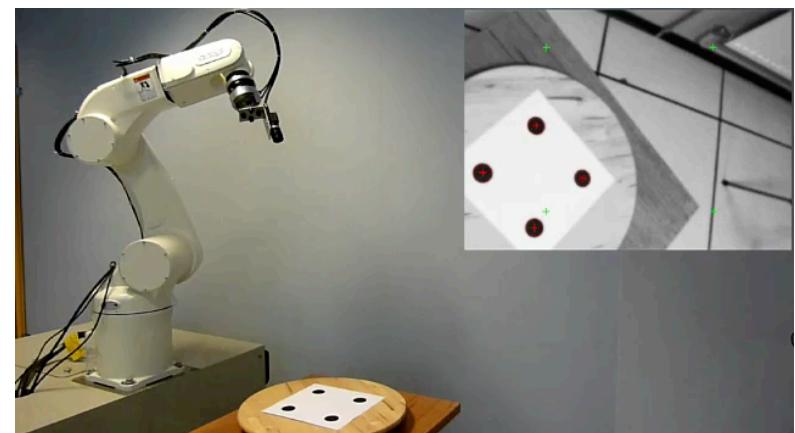
video



$$\dot{q} = \hat{J}^\#(Z^*)Ke$$



video



F. Chaumette, INRIA Rennes



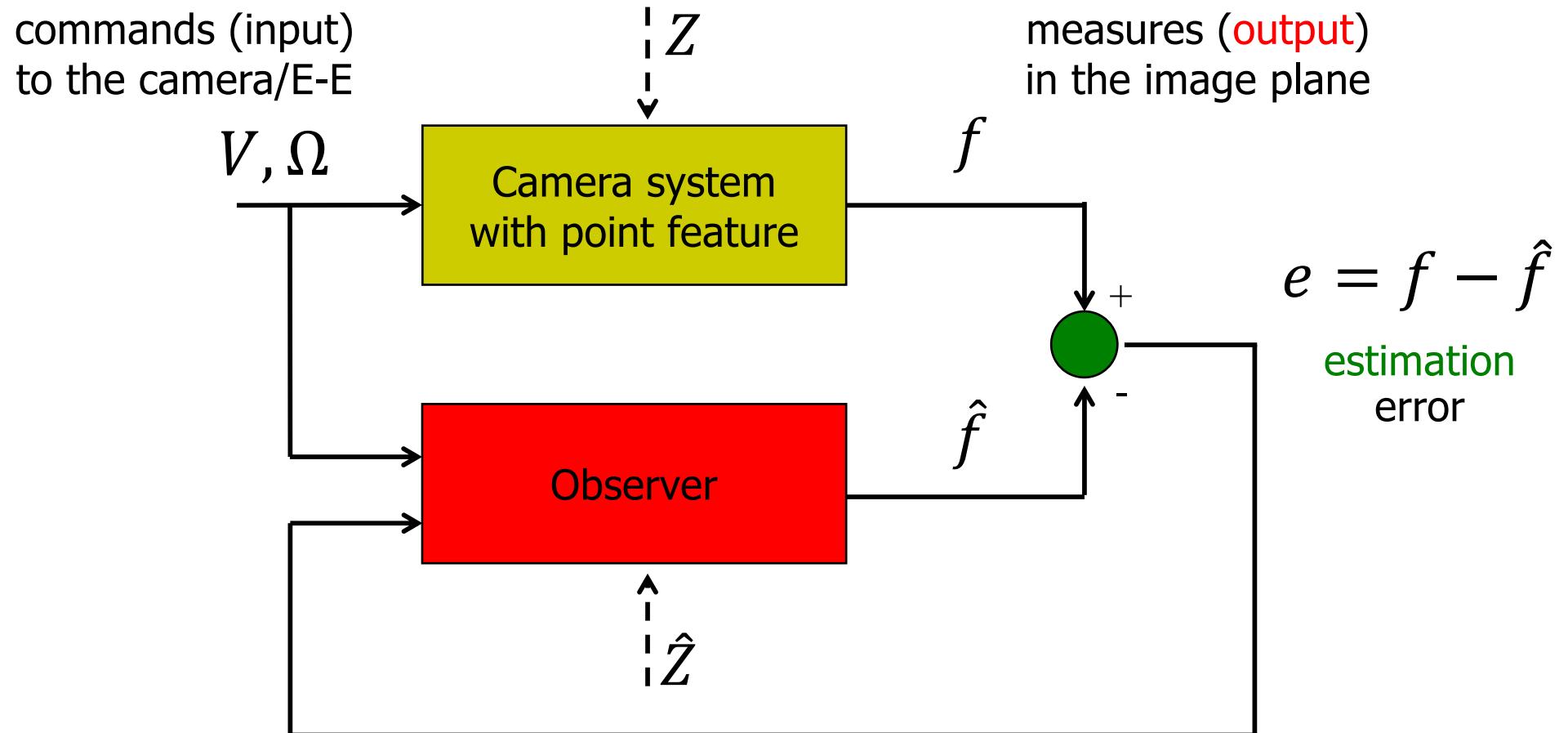
An observer of the depth Z

- it is possible to **estimate on line** the current value (possibly time-varying) of the depth Z , **for each** considered point feature, using a dynamic **observer**
- define $x = [u \ v \ 1/Z]^T$, $\hat{x} = [\hat{u} \ \hat{v} \ 1/\hat{Z}]^T$ as **current state** and **estimated state**, and $y = [u \ v]^T$ as **measured output**
- a (nonlinear) observer of x with input $u_c = [V \ \Omega]^T$
$$\dot{\hat{x}} = \alpha(\hat{x}, y)u_c + \beta(\hat{x}, y, u_c)$$
 guarantees $\lim_{t \rightarrow \infty} \|x(t) - \hat{x}(t)\| = 0$ **provided that**
 - **linear velocity** of the camera is **not** zero
 - the linear velocity vector **is not aligned** with the projection ray of the considered point feature

⇒ these are **persistent excitation** conditions (\sim observability conditions)



Block diagram of the observer





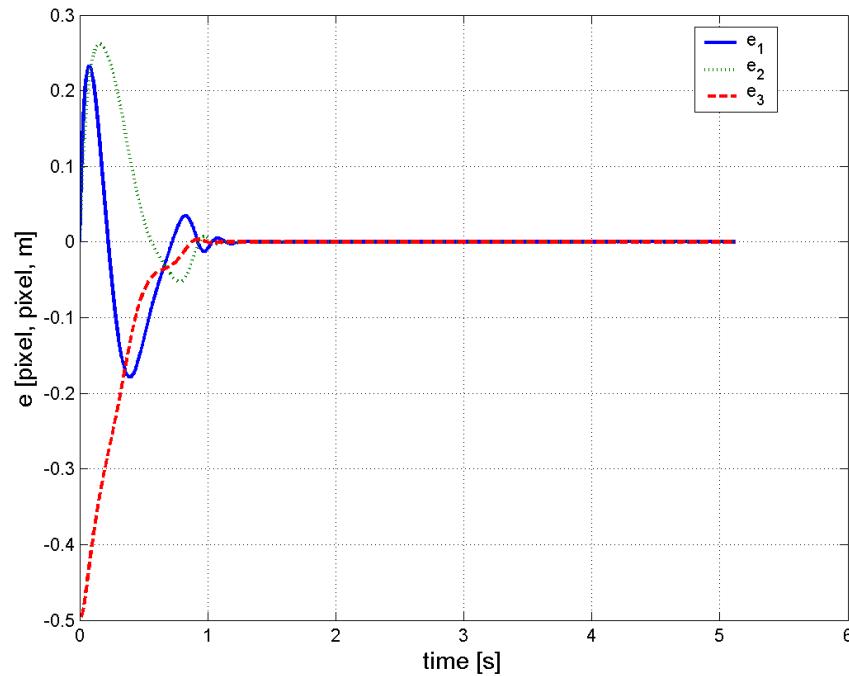
Results on the estimation of Z

real and estimated initial state

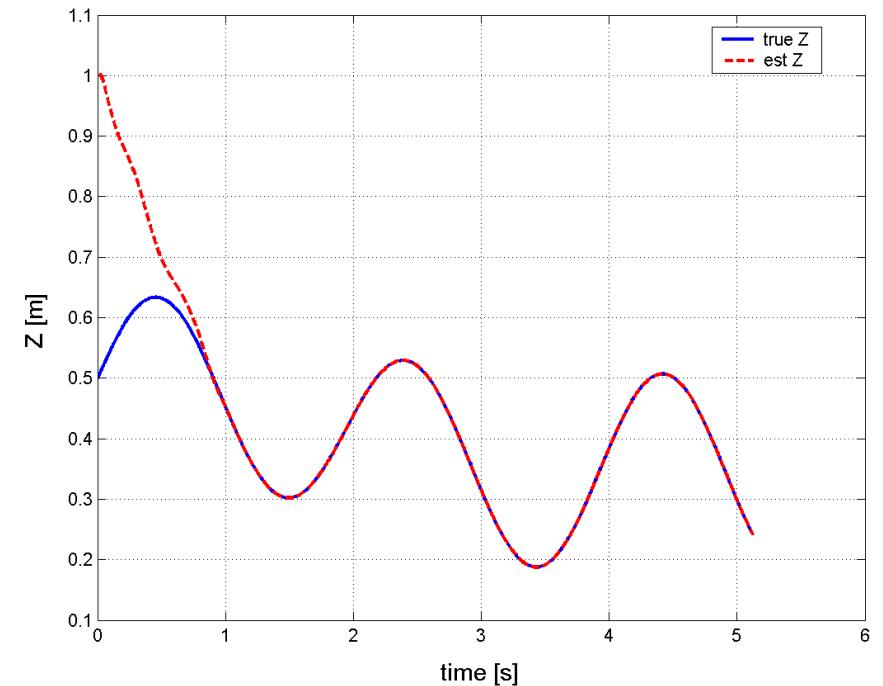
$$x(t_0) = [10 \quad -10 \quad 2]^T$$
$$\hat{x}(t_0) = [10 \quad -10 \quad 1]^T$$

$$v_x(t) = 0.1 \cos 2\pi t$$
$$v_z(t) = 0.5 \cos \pi t$$
$$\omega_x(t) = 0.6 \cos(\pi/2)t$$
$$\omega_z(t) = 1$$

open-loop
commands



estimation errors $e(t)$



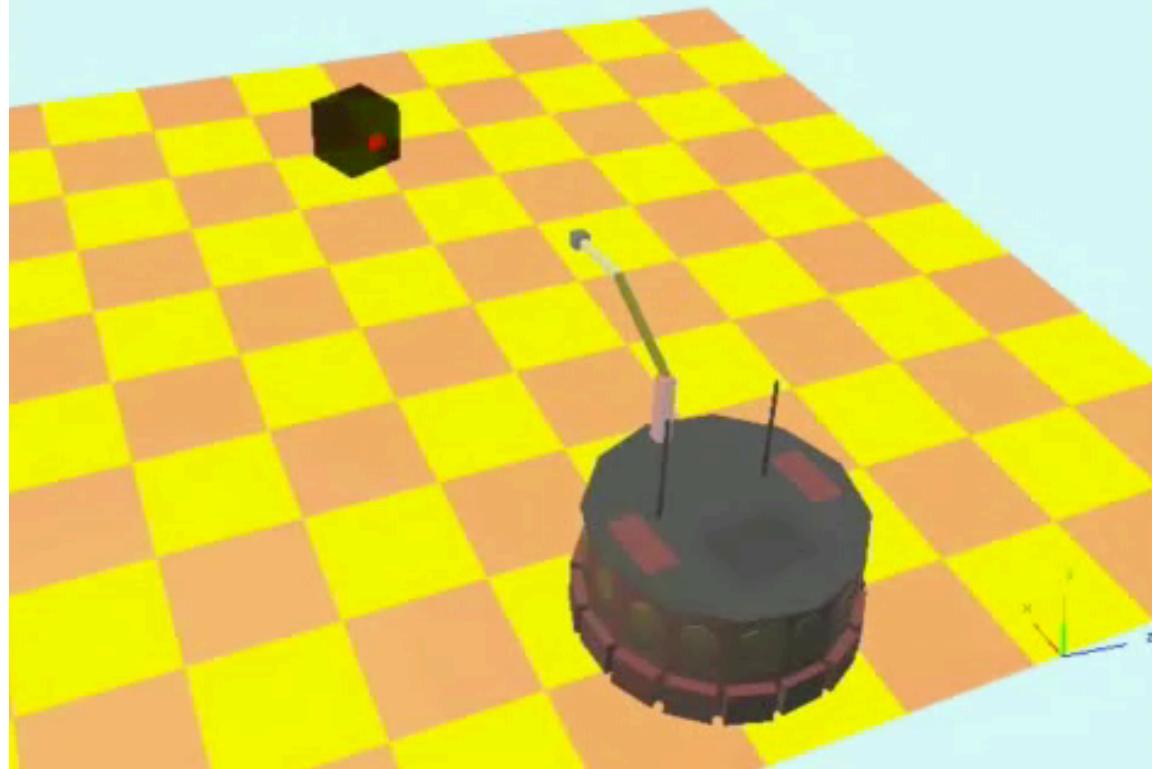
$Z(t)$ and $\hat{Z}(t)$



Simulation of the observer with stepwise displacements of the target

[video](#)

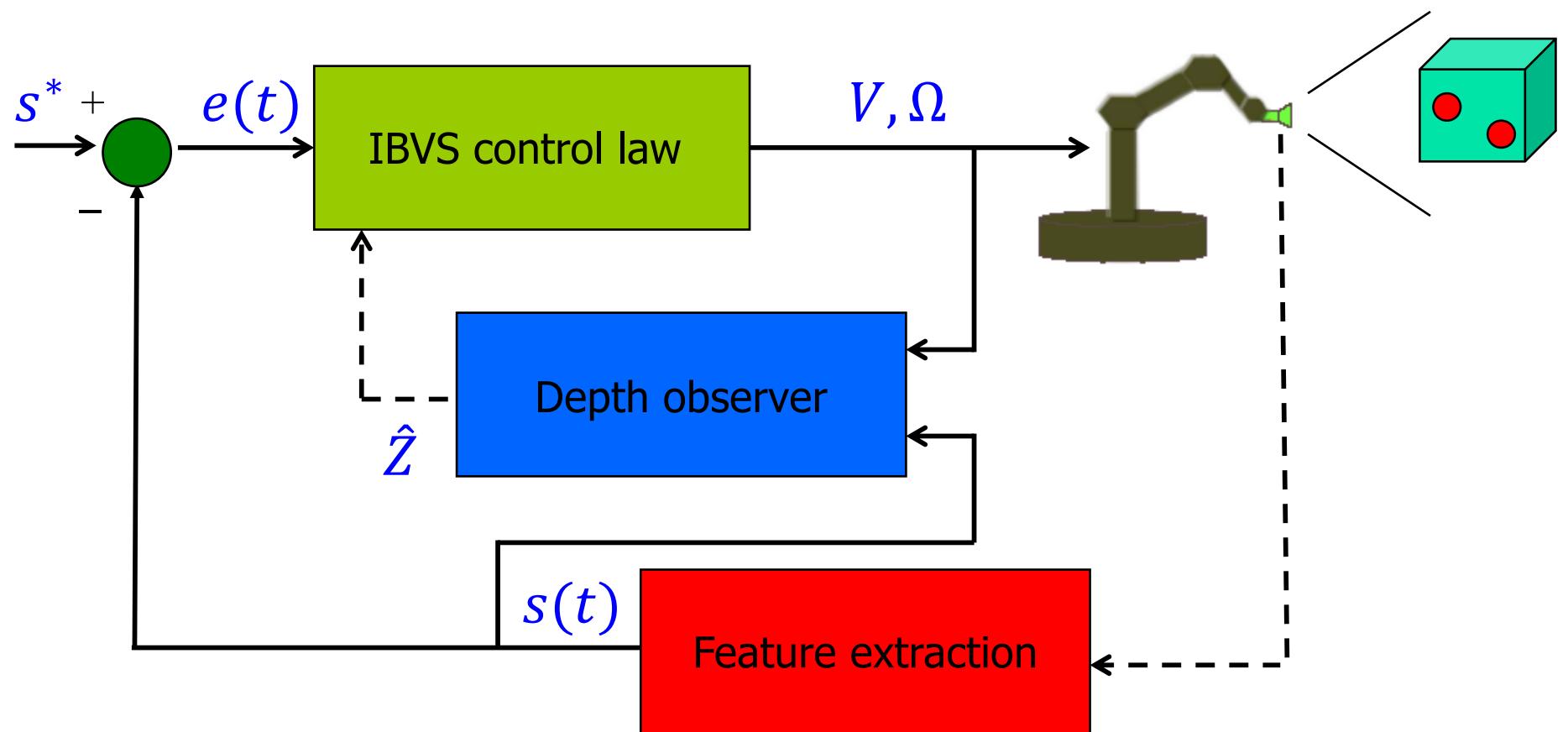
The crosshair represents the estimated value of the depth Z





IBVS control with observer

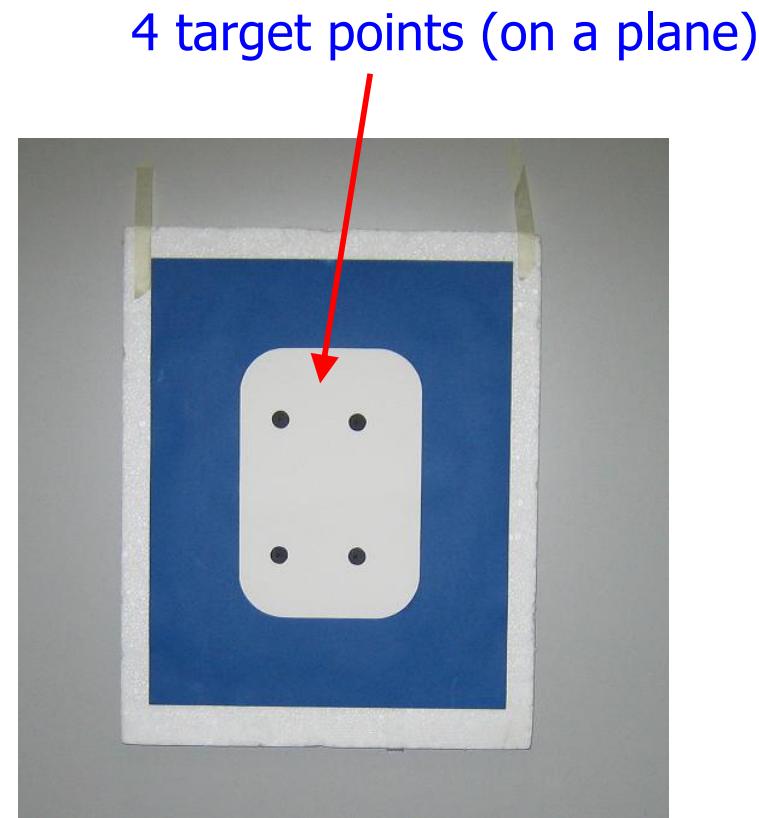
- the depth observer can be easily integrated on line with any IBVS control scheme





Experimental set-up

- visual servoing with fixed camera on a skid-steering mobile robot
- **very rough** eye-robot calibration
- **unknown** depths of target points (**estimated on line**)



a “virtual” 5th feature is also used
as the **average** of the four point features



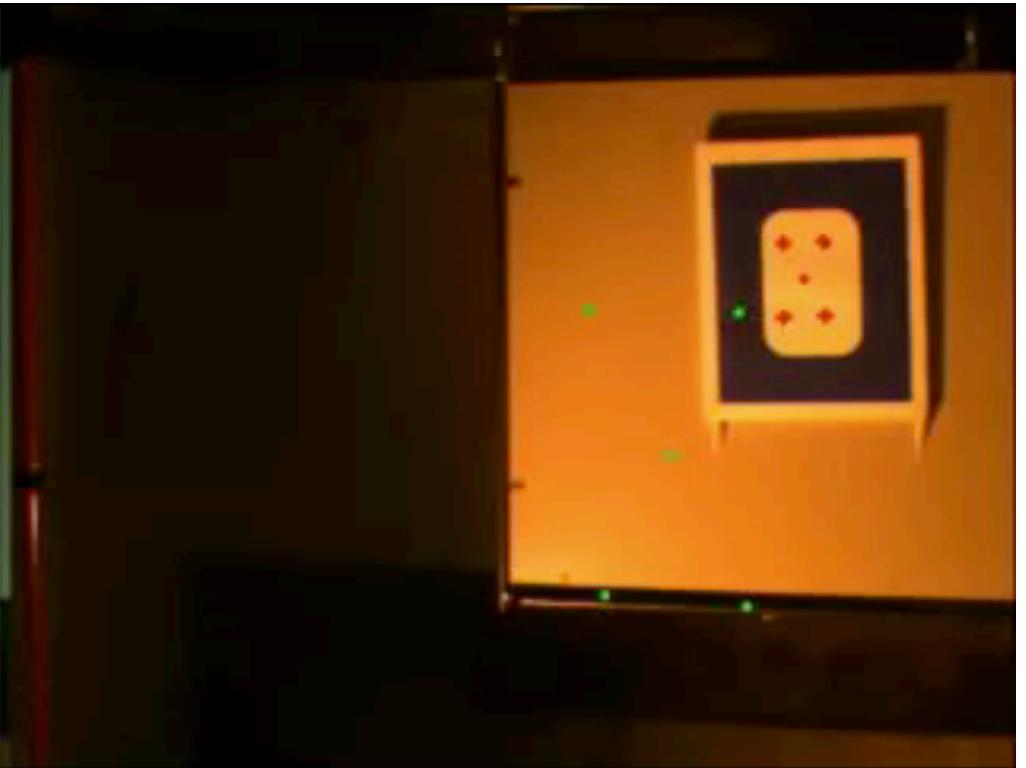
Experiments

- motion of features on the image plane is not perfect...
- the visual **regulation** task is however correctly **realized**

external view



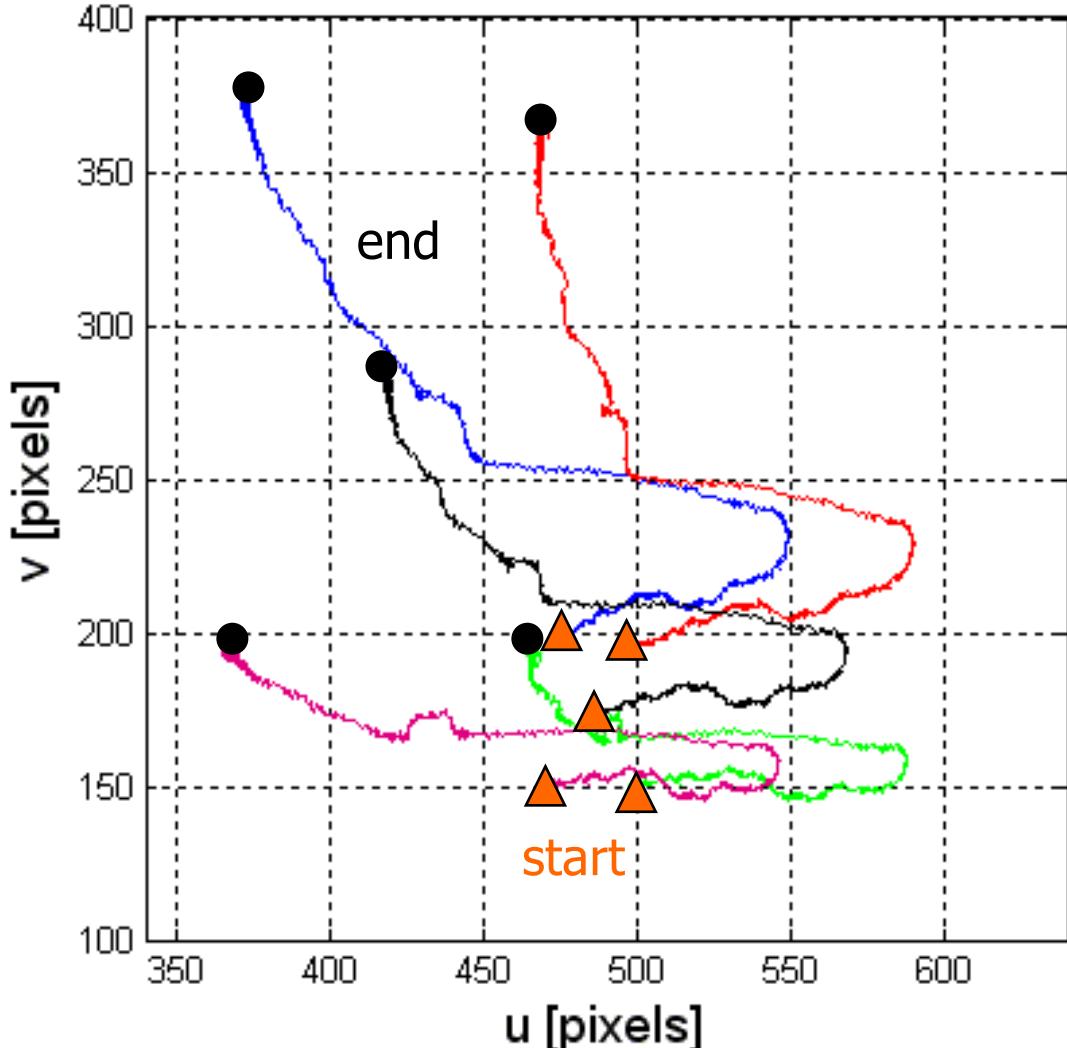
camera view



video (c/o Università di Siena)



Evolution of features



- motion of the 5 features (including the average point) in the image plane
- toward end, motion is \approx linear since the depth observers have already converged to the true values
- computed Image Jacobian is close to the actual one

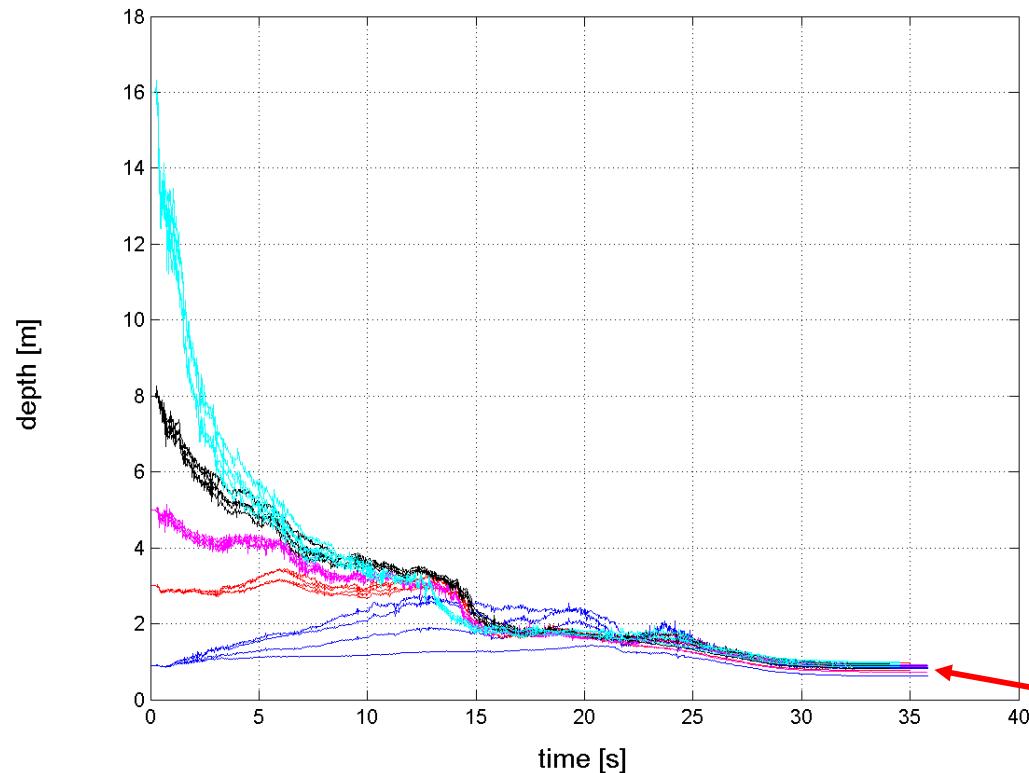
$$\hat{Z} \rightarrow Z \Rightarrow \hat{J} \rightarrow J$$

- “true” initial and final depths
- $$Z(t_0) \cong 4 \text{ m} \quad Z_d \cong 0.9 \text{ m}$$



Experiments with the observer

- the same task was executed with **five different initializations** for the depth observers, ranging between **0.9 m** (= true depth in the **final** desired pose) and **16 m** (much larger than in the true **initial** pose)



- initial values of depth estimates in the five tests

$$\left\{ \begin{array}{l} \hat{Z}_1(t_0) = 16 \text{ m} \\ \hat{Z}_2(t_0) = 8 \text{ m} \\ \hat{Z}_3(t_0) = 5 \text{ m} \\ \hat{Z}_4(t_0) = 3 \text{ m} \\ \hat{Z}_5(t_0) = 0.9 \text{ m} \end{array} \right. \quad \begin{array}{c} \text{cyan} \\ \text{black} \\ \text{magenta} \\ \text{red} \\ \text{blue} \end{array}$$

- true depths in initial pose

$$Z(t_0) \cong 4 \text{ m}$$

- true depths in final pose

$$Z_d \cong 0.9 \text{ m}$$

the evolutions of the **estimated** depths for the 4 point features



Visual servoing with Kuka robot set-up

- Kuka KR5 sixx R650 manipulator (6 revolute joints, spherical wrist)
- Point Grey Flea^{©2} CCD camera, eye-in-hand (mounted on a support)
- Kuka KR C2sr low-level controller (RTAI Linux and Sensor Interface)
- image processing and visual servoing on PC (Intel Core2 @2.66GHz)
- high-level control data exchange every **12ms** (via UDP protocol)



@ DIAG Robotics Laboratory

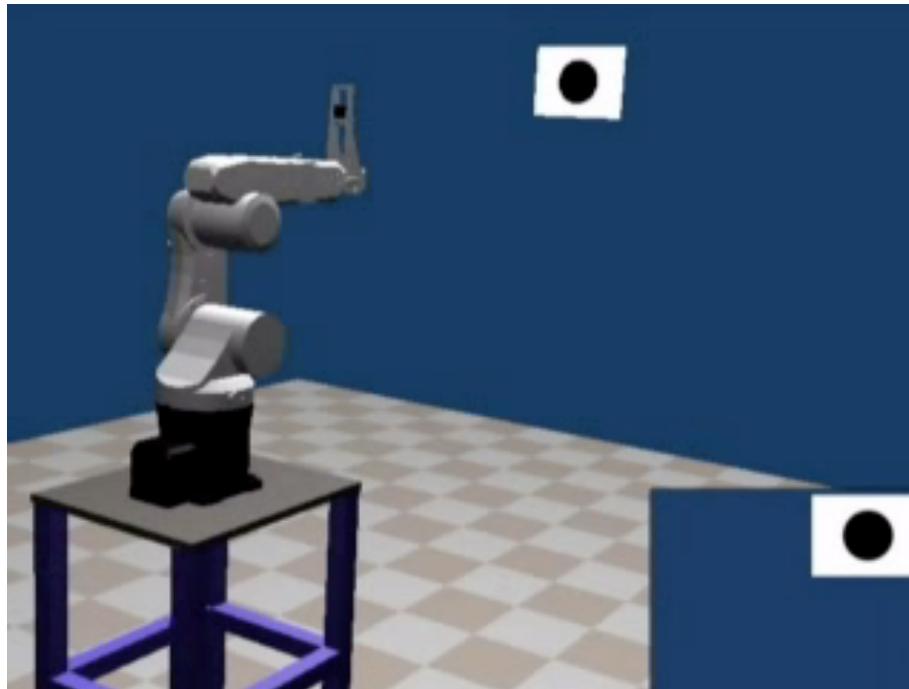


Visual servoing with Kuka robot

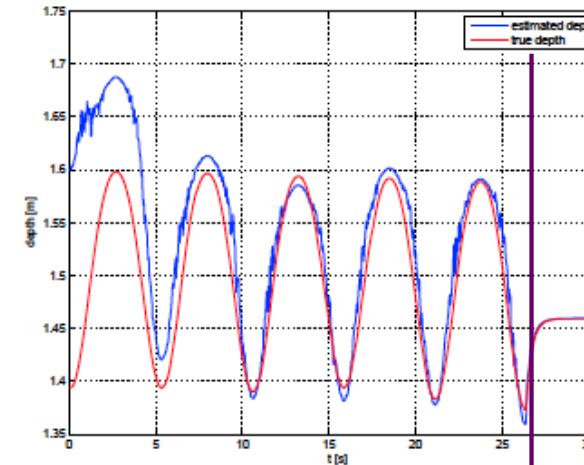
simulation and experiment with the observer

- depth estimation for a **fixed target** (single point feature)
- **simulation** using Webots first, then **experimental** validation
- **sinusoidal motion** of four robot joints so as to provide sufficient excitation

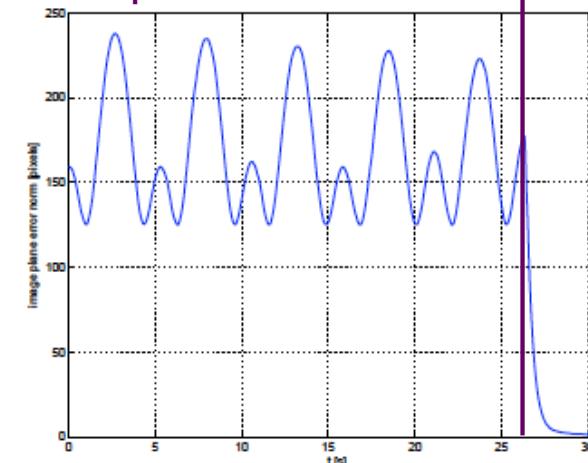
video



Webots simulation



Kuka experiment



true and estimated depth

norm of centering error of feature point [in pixels]



goes to zero once control is activated



Visual servoing with Kuka robot tracking experiment

- tracking a (slowly) time-varying target by visual servoing, including the depth observer (after convergence)



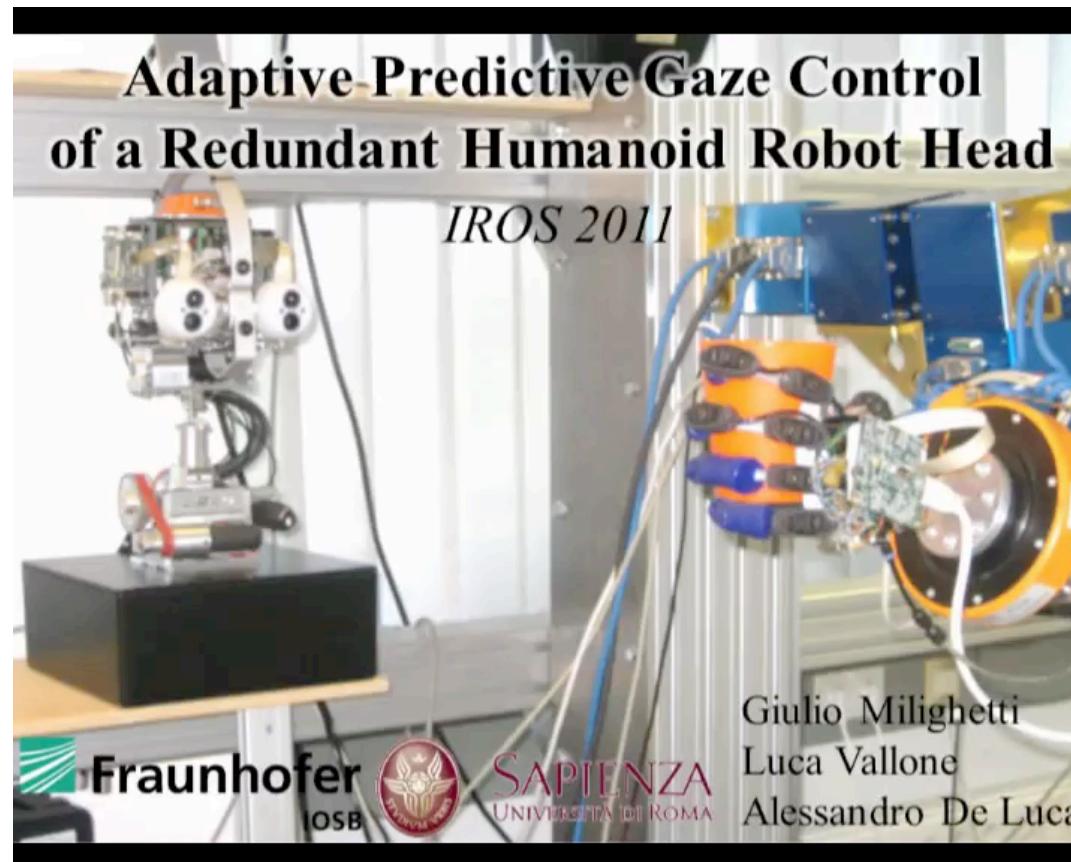
video



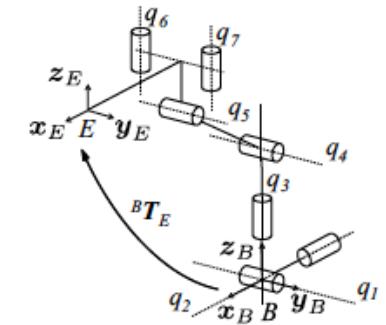
Gazing with humanoid head

stereo vision experiment

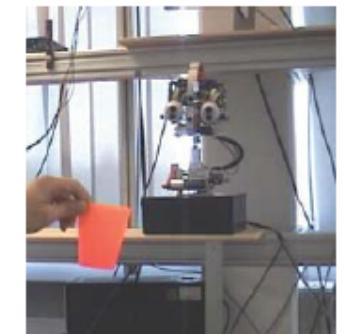
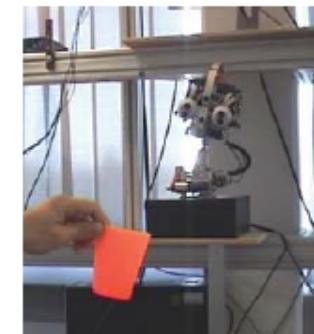
- gazing with a robotized head (7 joints, with $n = 6$ independently controlled) at a moving target (visual task dimension $m = 2$), using redundancy (to keep a better posture and avoid joint limits) and a predictive feedforward



video (c/o Fraunhofer IOSB, Karlsruhe)



$$\dot{\boldsymbol{q}} = \boldsymbol{J}_W^\dagger(\boldsymbol{q}) \left(\dot{\boldsymbol{\theta}}_{fb} + \dot{\boldsymbol{\theta}}_{ff} \right) - k_0 \left(\boldsymbol{I} - \boldsymbol{J}_W^\dagger(\boldsymbol{q}) \boldsymbol{J}(\boldsymbol{q}) \right) \nabla_{\boldsymbol{q}} H_0(\boldsymbol{q})$$



final head posture
without and with self-motions