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Surgical robotics – Montpellier, September 2005

VISUAL SERVOING
with applications in medical robotics

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Overview

- **Part I : Fundamentals of visual servoing**
  - **Background and definitions**
  - **Servoing architectures and classification**
  - **Position-based visual servoing**
  - **Image-based visual servoing**
- **Part II : Medical robotics applications**
  - **Laparoscopic surgery**
  - **Internal organ motion tracking**

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A. Coordinates and pose

- **Coordinates of point P with respect to coordinate frame i :**

$$^{i}P$$

- **Position and orientation of frame i with respect to frame j :**

$$\textit{Pose} = {}^{j}p_i = \begin{bmatrix} T_x \\ T_y \\ T_z \\ a \\ b \\ g \end{bmatrix}$$

T_x, T_y, T_z: translation vector $= {}^{j}O_i$ — *origin of frame* i *w.r.t. to frame* j

a, b, g: rotation angles $\Rightarrow {}^{j}R_i$ — *rotation matrix*

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B. Coordinate transformations

- **Coordinates of point** ^{i}P **with respect to coordinate frame** j **:**

$$^{j}P = {}^{j}O_i + {}^{j}R_i\,{}^{i}P$$

- **Coordinates of vector** ^{i}V **with respect to frame** j **:**

$$^{j}V = {}^{j}R_i\,{}^{i}V$$

- **Homogeneous transformation from frame** i **to frame** j **:**

$$^{j}H_i = \begin{bmatrix} ^{j}R_i & ^{j}O_i \\ 0 & 1 \end{bmatrix} \Rightarrow \begin{bmatrix} ^{j}P \\ 1 \end{bmatrix} = {}^{j}H_i \begin{bmatrix} ^{i}P \\ 1 \end{bmatrix} \qquad \begin{bmatrix} ^{j}V \\ 0 \end{bmatrix} = {}^{j}H_i \begin{bmatrix} ^{i}V \\ 0 \end{bmatrix}$$

$$^{j}H_i = {}^{j}H_k\,{}^{k}H_i$$

C. Velocity of a rigid object

- **Velocity screw of frame *i* with respect to frame *j* in frame *j* coordinates:**

$$ {}^{j}\left({}^{j}\dot{r}_{i}\right) = \begin{bmatrix} v_x \\ v_y \\ v_z \\ w_x \\ w_y \\ w_z \end{bmatrix} \quad \begin{matrix} \left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} \text{translational velocity} = {}^{j}\left({}^{j}V_{i}\right) \\ \left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} \text{rotational velocity} = {}^{j}\left({}^{j}\Omega_{i}\right) \end{matrix} $$

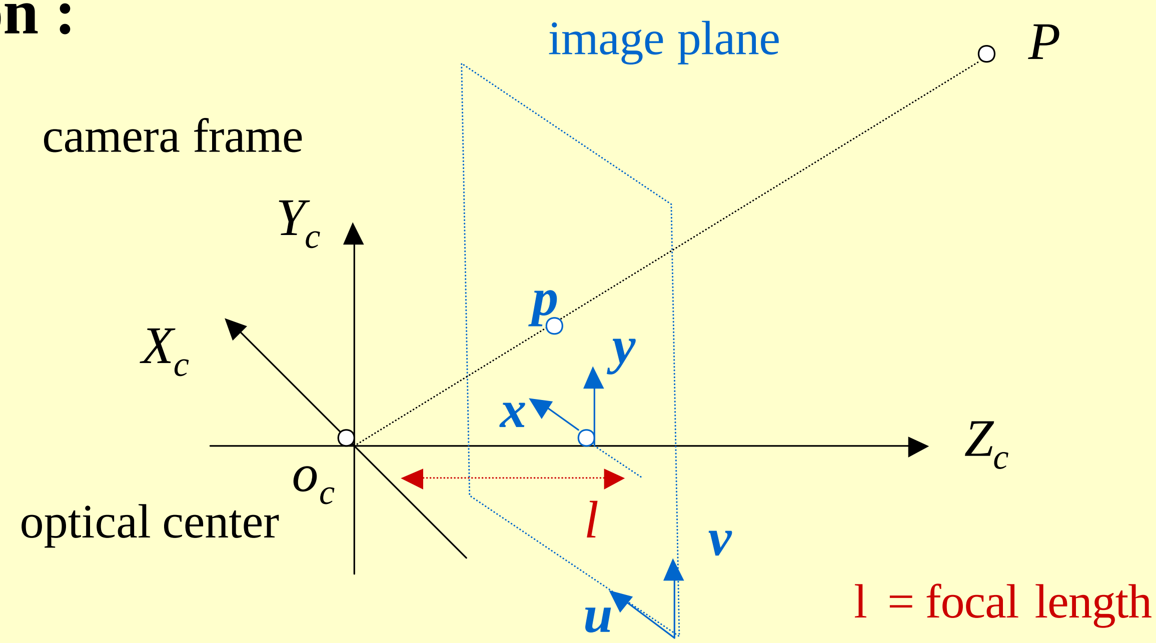
- **Velocity of point *P* rigidly attached to frame *i* with respect to frame *j* expressed in frame *j* coordinates :**

$$ {}^{j}\dot{P} = {}^{j}\left({}^{j}\Omega_{i}\right) \times {}^{j}P + {}^{j}\left({}^{j}V_{i}\right) = {}^{j}\left({}^{j}\Omega_{i}\right) \times \left({}^{j}R_{i}\,{}^{i}P + {}^{j}O_{i}\right) + {}^{j}\left({}^{j}V_{i}\right) $$

D. Camera projection model

Perspective projection :

(other models apply for other type of visual sensors, e.g., C-arm, CT-scan, ultrasound probe, …)



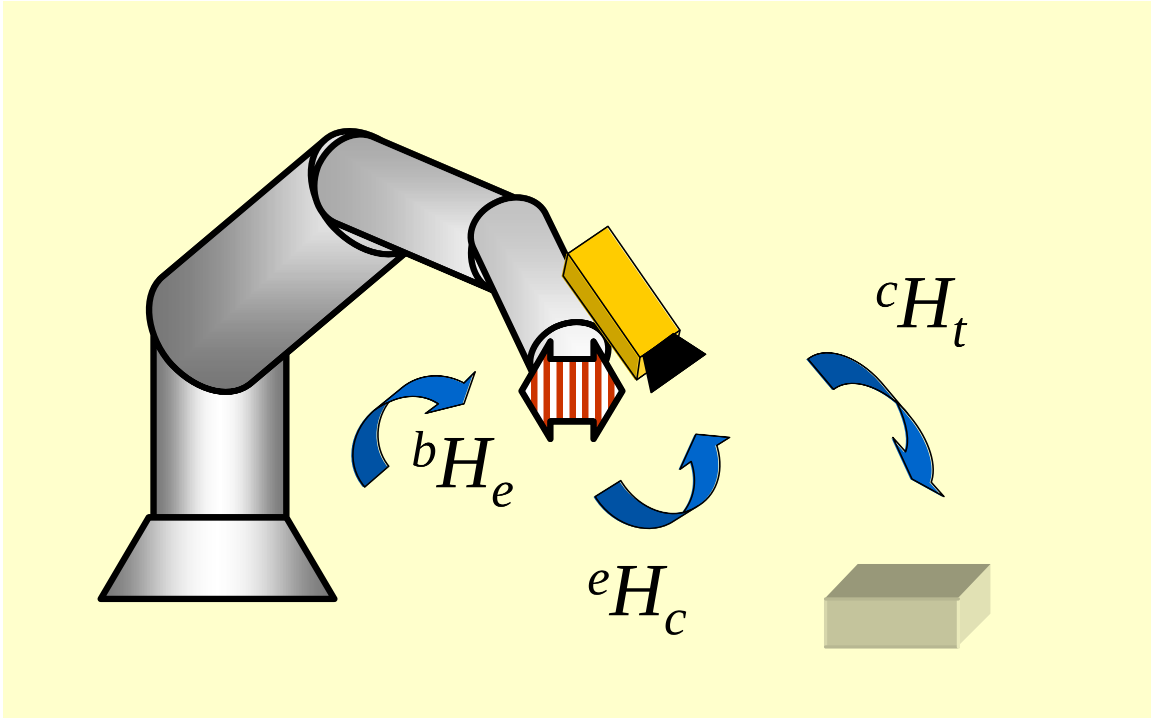
${}^cP$ **= coordinates of point** P **with respect to the camera frame** c

$$ {}^C P = \begin{bmatrix} x_c \\ y_c \\ z_c \end{bmatrix} \Rightarrow \begin{bmatrix} x \\ y \end{bmatrix} = l \begin{bmatrix} \frac{x_c}{z_c} \\ \frac{y_c}{z_c} \end{bmatrix} \Rightarrow \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} u_0 + l\, k_u \frac{x_c}{z_c} \\ v_0 + l\, k_v \frac{y_c}{z_c} \end{bmatrix} $$

pixels

Intrinsic camera parameters obtained by calibration

A. Eye-in-hand configuration



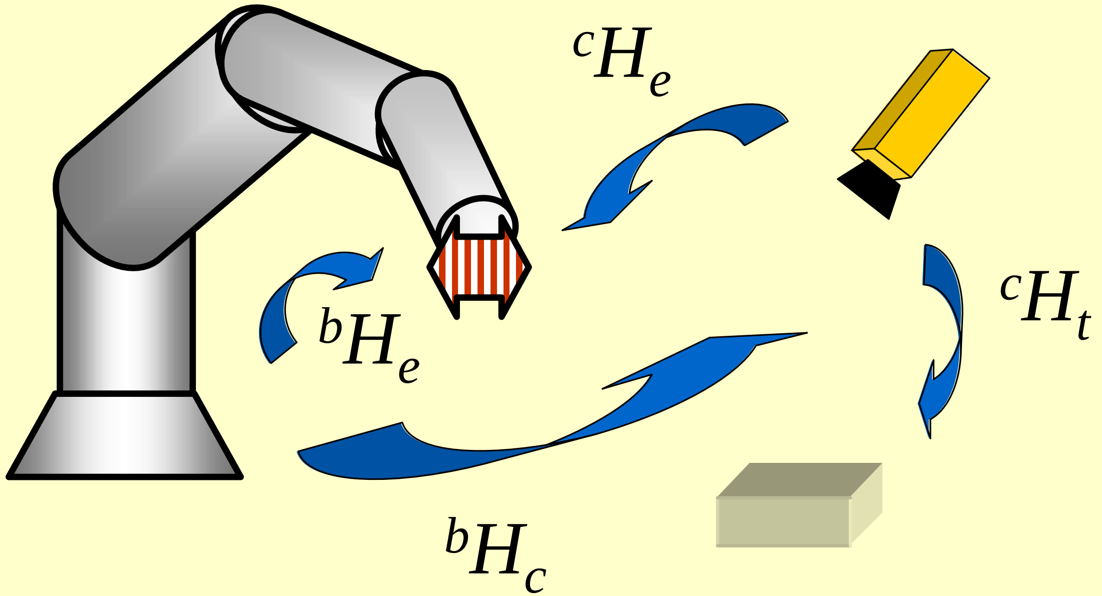
$$^eH_t = {}^eH_c\,{}^cH_t \qquad {}^bH_t = {}^bH_e\,{}^eH_t$$

^eH_c must be known

B. External camera configuration

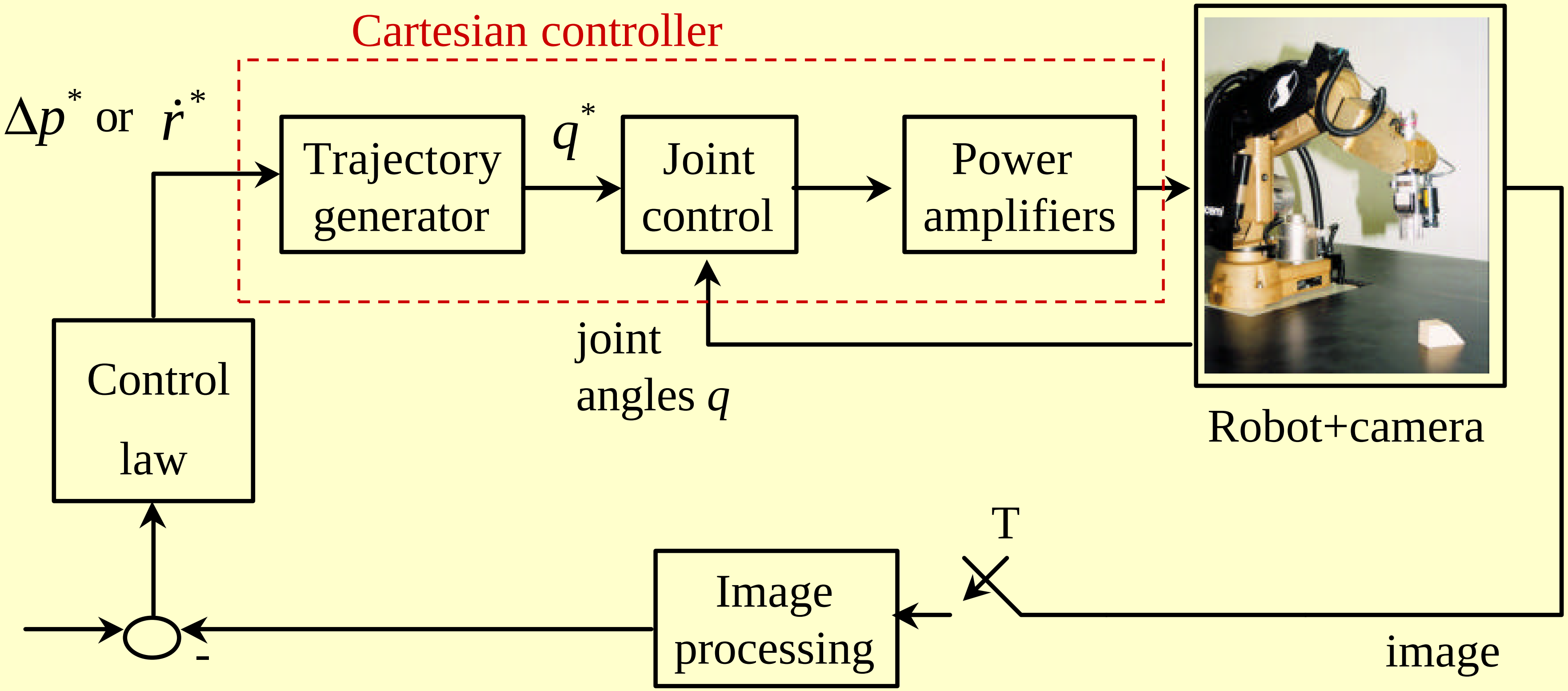
$^{c}H_{e}$ must be measured or

$^{b}H_{c}$ must be known



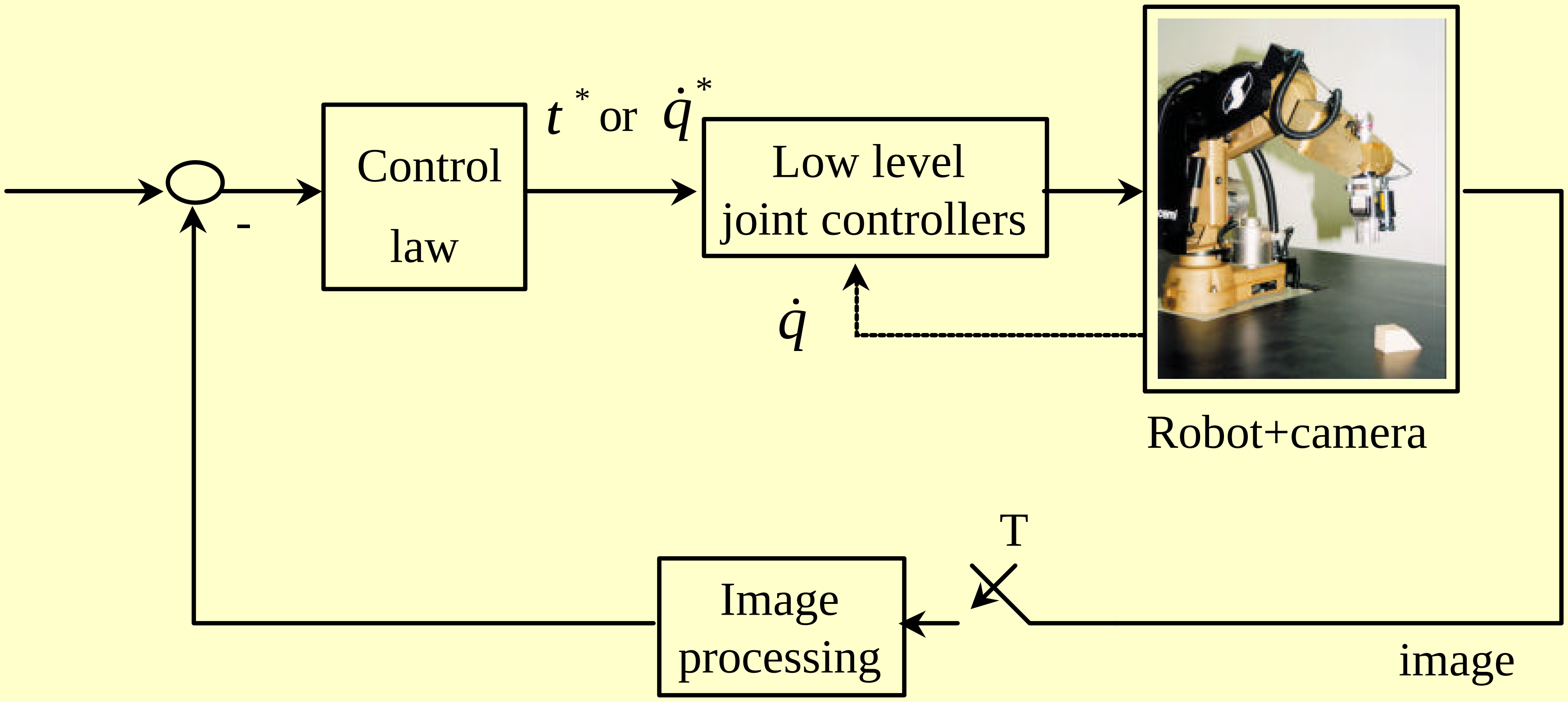
$$^{e}H_{t} = (^{c}H_{e})^{-1}\, ^{c}H_{t} \qquad ^{e}H_{t} = (^{b}H_{e})^{-1}\, ^{b}H_{c}\, ^{c}H_{t}$$

A. Indirect visual servoing



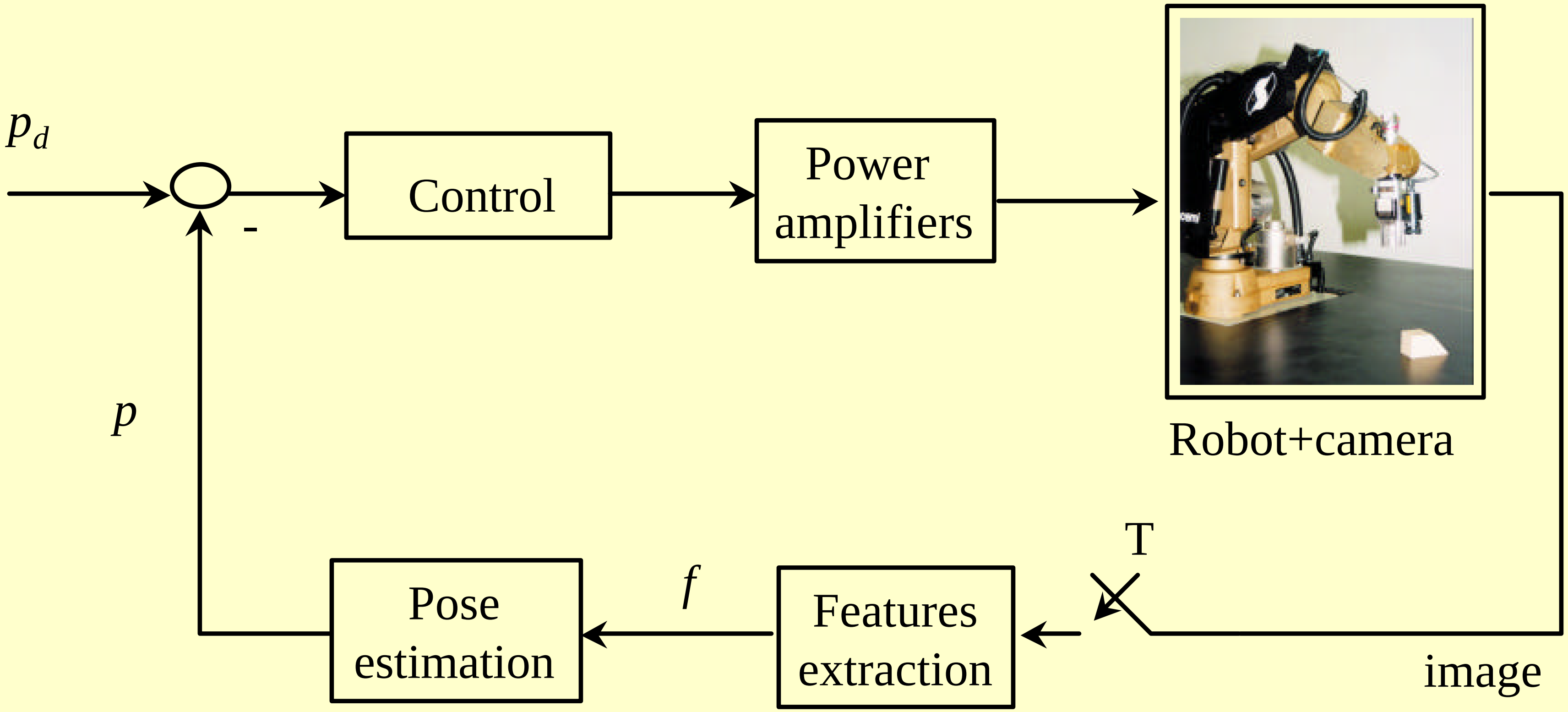
- Suitable for slow visual servoing ($T^{-1} < 50$ Hz)
- Control law is easier to design

B. Direct visual servoing



- Suitable for fast visual servoing (T^{-1} >= 50 Hz)
- Control law design is more complex (robot dynamics must be taken into account)

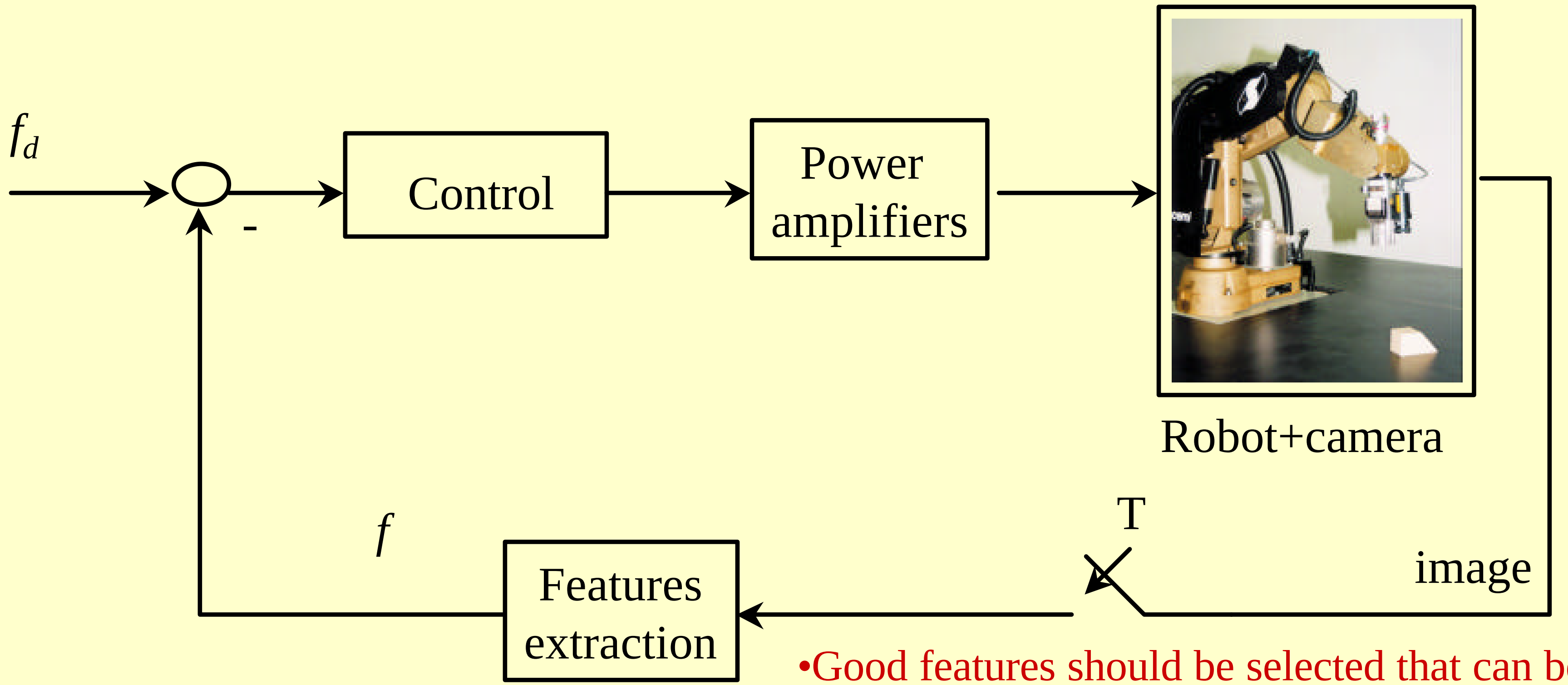
A. Position-based visual servoing (3D visual servoing)



- A model of the object must be known or multiple cameras should be used
- Calibration errors may induce large pose estimation errors
- Control law design is easier
- Possible loss of target for large errors

I.2 Classification
I.23 Feedback variables

B. Image-based visual servoing (2D visual servoing)

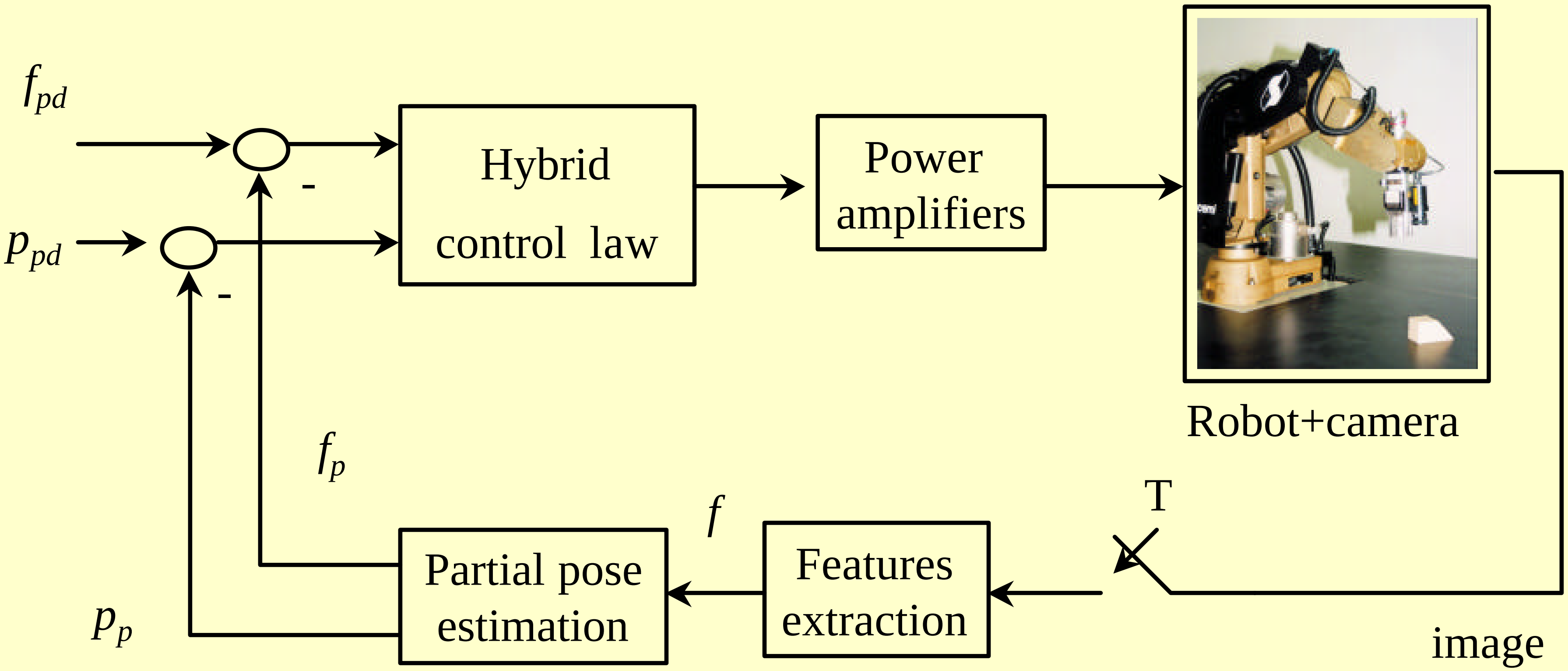


- Smaller computational burden
- Eliminates errors due to calibration
- More complex control law
- Workspace limits can be hit for large errors

- Good features should be selected that can be located unambiguously in the scene : *e.g.*, coordinates of points, centroïd of a projected surface, parameters of an ellipse in the image plane, …

I.2 Classification
I.23 Feedback variables

C. Hybrid visual servoing (2D1/2 visual servoing)

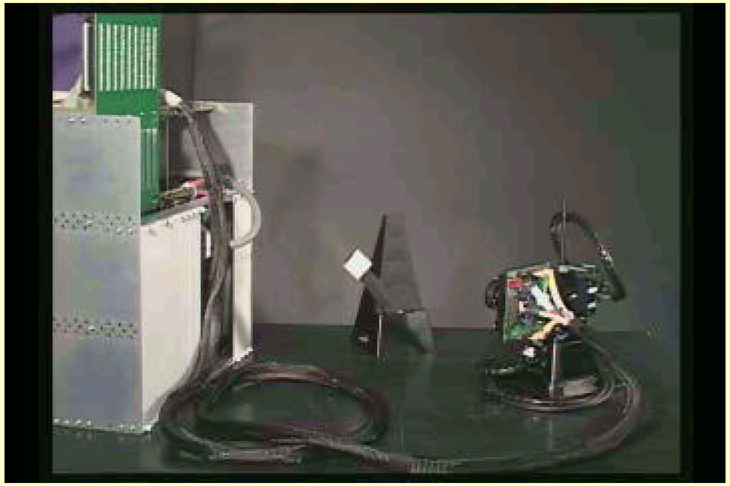


- Smaller errors due to calibration
- Simplified model of the target
- Better properties of the control law (solutions exist for large motions)

I.24 Bandwith of the visual servo-loop

A. Slow visual servoing

- Sampling frequency < 50Hz
- Indirect visual servoing
- Robot transfer function model without dynamics
- Proportional control law (P)



B. Fast visual servoing

- Sampling frequency >= 50 Hz
- Direct visual servoing
- Dynamical model of the robot must be taken into account
- More advanced control laws : PID, predictive, robust, non-linear, …

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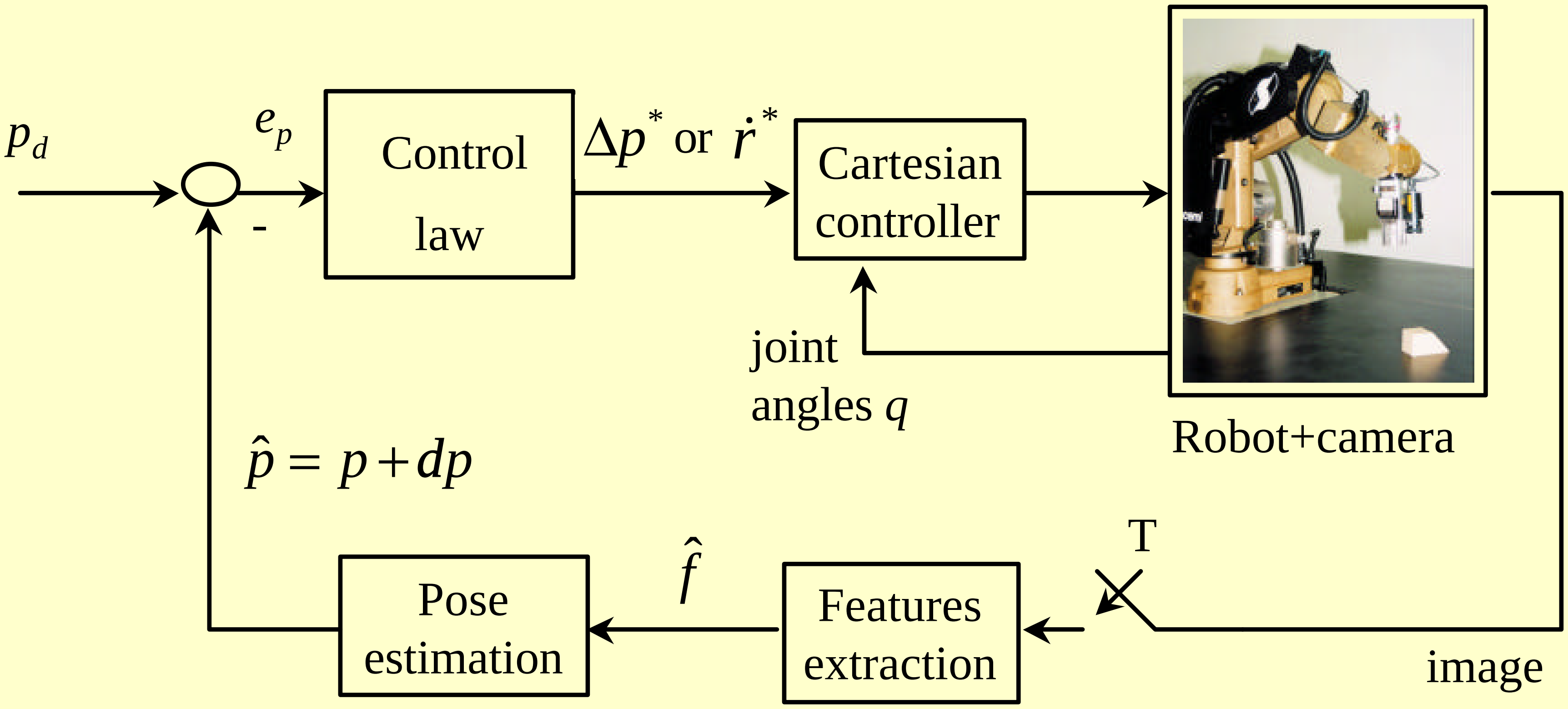
I.3 Position-based visual servoing
I.31 Indirect visual servoing

A. Control law



- Look-then-move strategy (T very large, asynchronous) : $\Delta p^* = e_p$
- Pseudo-continuous strategy : $\dot{p} = J_p^T \ \dot{r}$ ⇨ Control law : $\dot{r}^* = k \ J_p^{T^{-1}} \ e_p$

B. Stability and robustness

Stability is not an issue : Look-then-move strategy is always stable and low vision-loop bandwidth: ⇒ $\dot{r} \approx \dot{r}^*$ ⇒ $\dot{p} = k\, J_p^T\, J_p^{T^{-1}} e_p$ ⇒ Exponential convergence

Measurement error is an issue: dp can be very large !

- Camera calibration : *Tsaï (IEEE Trans. Rob. Aut., 1987)*
- Pose estimation :
  - •Monocular vision algorithms using 3 or 4 points : *Tsaï (co-planar target) or DeMenthon (IEEE Trans. PAMI 1992, Int. J. Comp. Vision 1995)*
  - •Multiple cameras

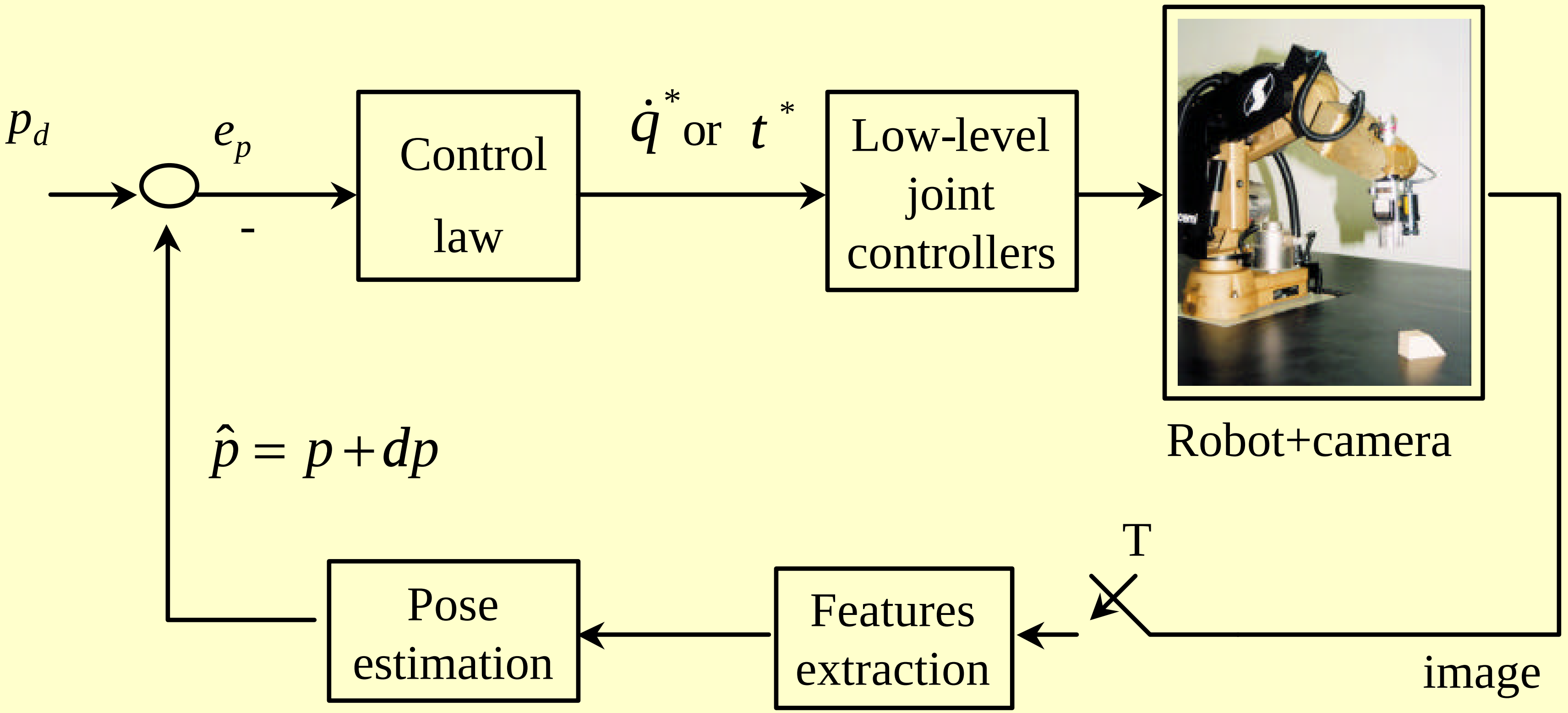
-Main sources of uncertainty :

⇒Improvement: use learning of p_c when possible

- Camera intrinsic parameters
- Camera position w.r. to end-effector if eye-in-hand configuration
- Camera position w.r. to the robot base and robot kinematic chain if external camera, except if end-effector pose is estimated by vision
- Feature detection error : $df = \hat{f} - f$

I.3 Position-based visual servoing
I.32 Direct visual servoing

A. Control law



$$\dot p = J_p^T \dot r = J_p^T \; J_R(q)\, \dot q \quad \Rightarrow \quad \text{Control law : } \dot q^* = k\, J_R^{-1}(q)\, J_p^{T^{-1}} e_p$$

B. Stability and robustness (1)

Stability may be an issue:

- Low bandwidth vision loop : ⇨ $\dot{q} \approx \dot{q}^*$

⇨ $$\dot{p} = kJ_p^T \; J_R(q) \; J_R^{-1}(q) J_p^{T^{-1}} e_p$$ ⇨ Exponential convergence

- High bandwidth vision loop :
  - Linearized approach : $\dot{q}(s) \approx F(s,q)\,\dot{q}^*(s)$

⇨ $$p \approx \frac{1}{s} J_p^T J_R(q)\, F(s,q)\dot{q}^*$$

Joint-level velocity feedback loops have a linearizing and decoupling effect

⇨ Control law: $\dot{q}^* = J_R^{-1}(q)\, J_p^{T^{-1}} \dot{p}^*$ with $\dot{p}^*$ computed using a LPV discrete-time model of the vision loop

This approach works in practice with 6DOF vision loop !

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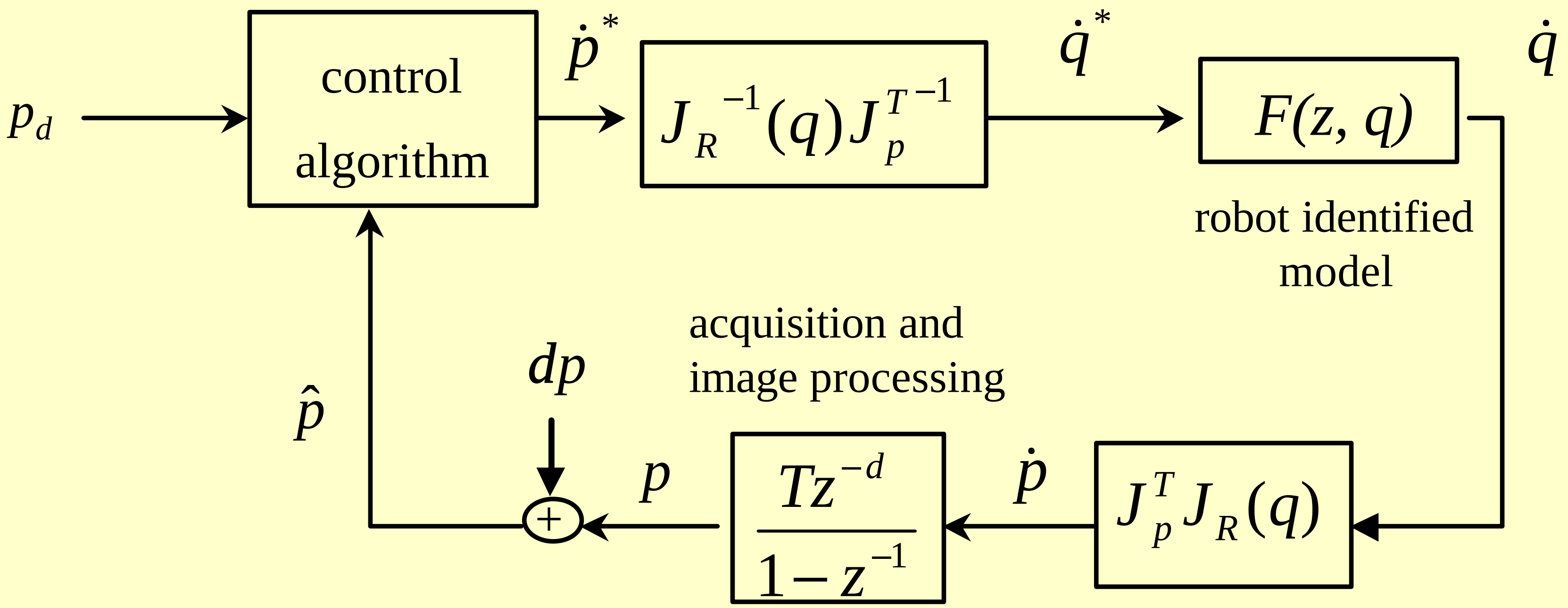
B. Stability and robustness (2)

LPV discrete-time model



GPC of a 6DOF robot vision loop :
J. Gangloff & M. de Mathelin (Advanced Robotics, vol 17, no 10, déc. 2003)

B. Stability and robustness (3)

- Non linear approach : rigid link robot manipulator model

$$t = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + f_r(q,\dot{q})$$

Inertia ↑ Coriolis, centripetal ↑ gravity ↑ friction ↑

- PD control scheme *(Arimoto)*: $t^* = g(q) - K_v\dot{q} - K_p e_q$ with $e_q = q - q_d$

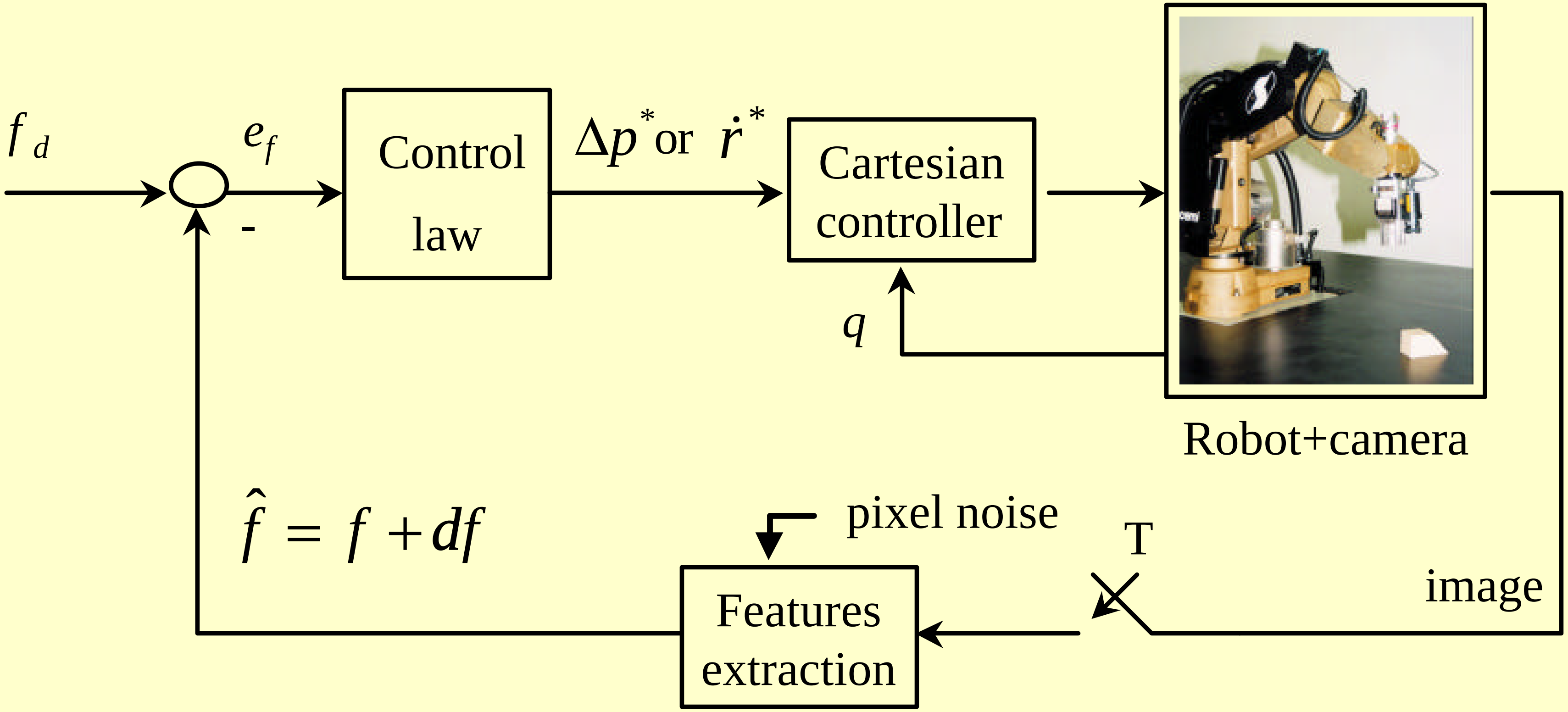
- Passivity-based scheme *(Slotine & Li):* $z = \dot{q}_d - \Lambda e_q$

$$t^* = M(q)\dot{z} + C(q,\dot{q})z + g(q) - K_v\dot{e}_q - K_p e_q$$

High complexity for 6DOF !

⇨ Problems: - asymptotic stability is proved with no friction
- q_d and $\dot{q}_d$ are generally unknown
- joint flexibilities and backlash

A. Control law



- Look-then-move strategy : select Δp^* or Δq^* to decrease a cost function of e_f
- Pseudo-continuous strategy : $\dot{f} = J_I \, \dot{r}$ ⇨ Control law : $\dot{r}^* = k \, J_I^+ \, e_f$

B. Stability and robustness (1)

Low bandwidth : $\dot{r} \approx \dot{r}^*$

⇒ $\dot{f} = k\, J_I\, J_I^{+} e_f$ ⇒ Exponential convergence

Image Jacobian or Interaction matrix : J_I

Exemple : case of a point ${}^cP$ rigidly attached to the end-effector moving with respect to a fixed camera, and whose coordinates are expressed in the camera frame

$$ {}^cP = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad {}^c({}^c\dot{r}_e) = \begin{bmatrix} v_x \\ v_y \\ v_z \\ w_x \\ w_y \\ w_z \end{bmatrix} $$

$$ {}^c\dot{P} = {}^c({}^c\Omega_e) \times {}^cP + {}^c({}^cV_e) $$

⇒

$$ {}^c\dot{P} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} z w_y - \frac{(v - v_0) z}{l k_v} w_z + v_x \\ \frac{(u - u_0) z}{l k_u} w_z - z w_x + v_y \\ \frac{z}{l} \left(\frac{(v - v_0)}{k_v} w_x - \frac{(u - u_0)}{k_u} w_y \right) + v_z \end{bmatrix} $$

image coordinates in pixel: (u,v) (cf. camera projection model)

B. Stability and robustness (2)

$$\Rightarrow \begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} \frac{l k_u}{z} & 0 & -\frac{(u-u_0)}{z} & -\frac{(u-u_0)(v-v_0)}{l k_v} & \frac{(l k_u)^2+(u-u_0)^2}{l k_u} & -\frac{k_u (v-v_0)}{k_v} \\ 0 & \frac{l k_v}{z} & -\frac{(v-v_0)}{z} & -\frac{(l k_v)^2+(v-v_0)^2}{l k_v} & \frac{(u-u_0)(v-v_0)}{l k_u} & \frac{k_v (u-u_0)}{k_u} \end{bmatrix} {}^c({}^c\dot{r}_e)$$

$$\Leftrightarrow \dot{f} = \begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = J_I\, {}^c({}^c\dot{r}_e)$$

Select N points with N>3 ⇒ J_I is full rank

Main source of uncertainty : J_I ⇒ $\hat{J}_I$ ⇒ $\dot{f} = k\, J_I\, \hat{J}_I^{+} e_f$

⇒ Exponential convergence if $J_I\, \hat{J}_I^{+} > 0$

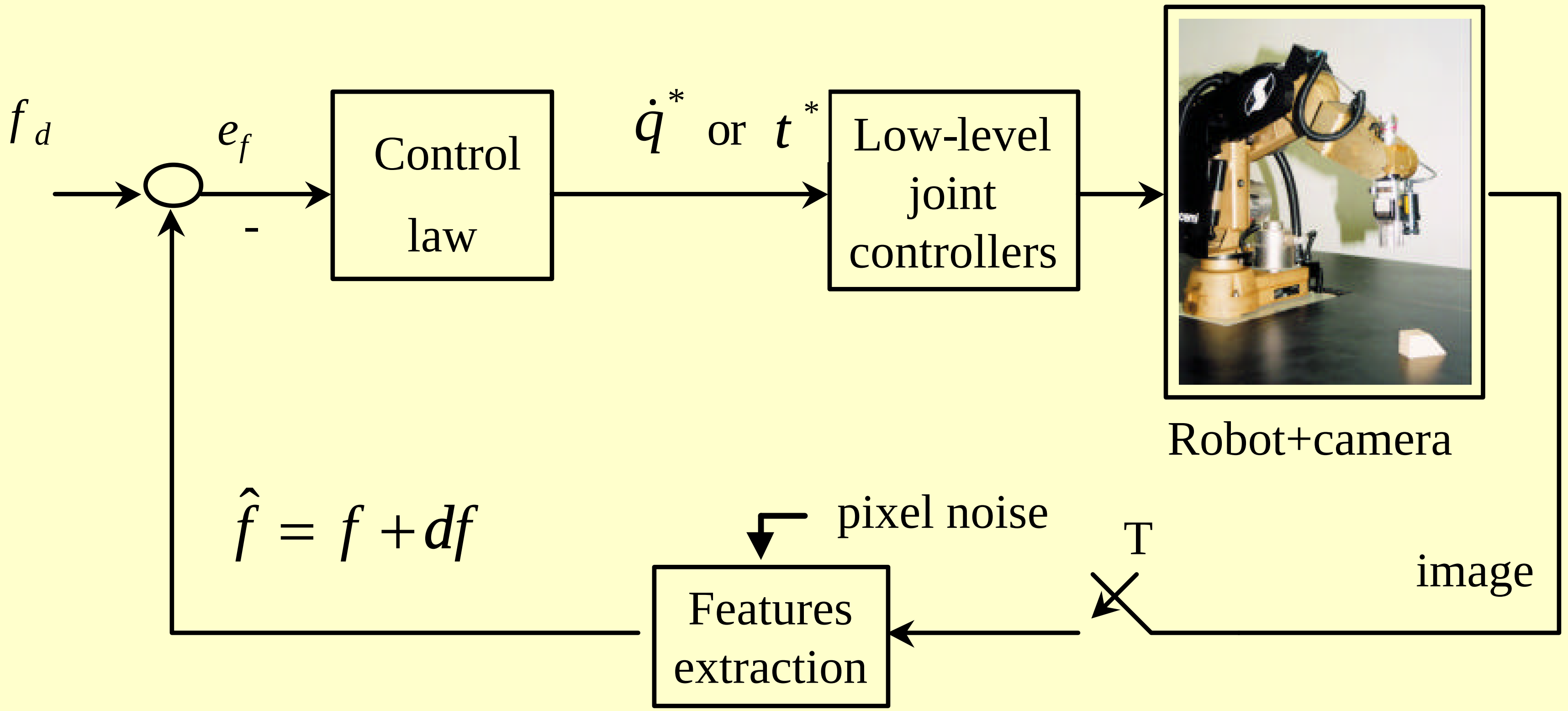
Pixel noise attenuation : pick more features ⇒ smaller df

Note also that f_d may be learned

Problem of reaching the workspace limits ⇒ Hybrid visual servoing

I.4 Image-based visual servoing
I.42 Direct visual servoing

A. Control law



$$\dot{f} = J_I \dot{r} \quad = J_I J_R(q)\,\dot{q} \quad \Rightarrow \quad \text{Control law :} \quad \dot{q}^* = k\, J_R^{-1}(q)\, \hat{J}_I^{+} e_f$$

B. Stability and robustness (1)

Stability may be an issue:

- Low bandwidth vision loop : ⇨ $\dot{q} \approx \dot{q}^*$

⇨ $\dot{f} = k\, J_I J_R(q)\, J_R^{-1}(q) \hat{J}_I^{+} e_f$ ⇨ Exponential convergence if $J_I\, \hat{J}_I^{+} > 0$

- High bandwidth vision loop :
  - Linearized approach : $\dot{q}(s) \approx F(s,q)\, \dot{q}^*(s)$

⇨ $f \approx \frac{1}{s} J_I J_R(q)\, F(s,q) \dot{q}^*$

⇨ Control law: $\dot{q}^* = J_R^{-1}(q)\, \dot{r}^*$ with $\dot{r}^*$ computed using a LPV discrete-time model of the vision loop

This approach works in practice with 6DOF vision loops !

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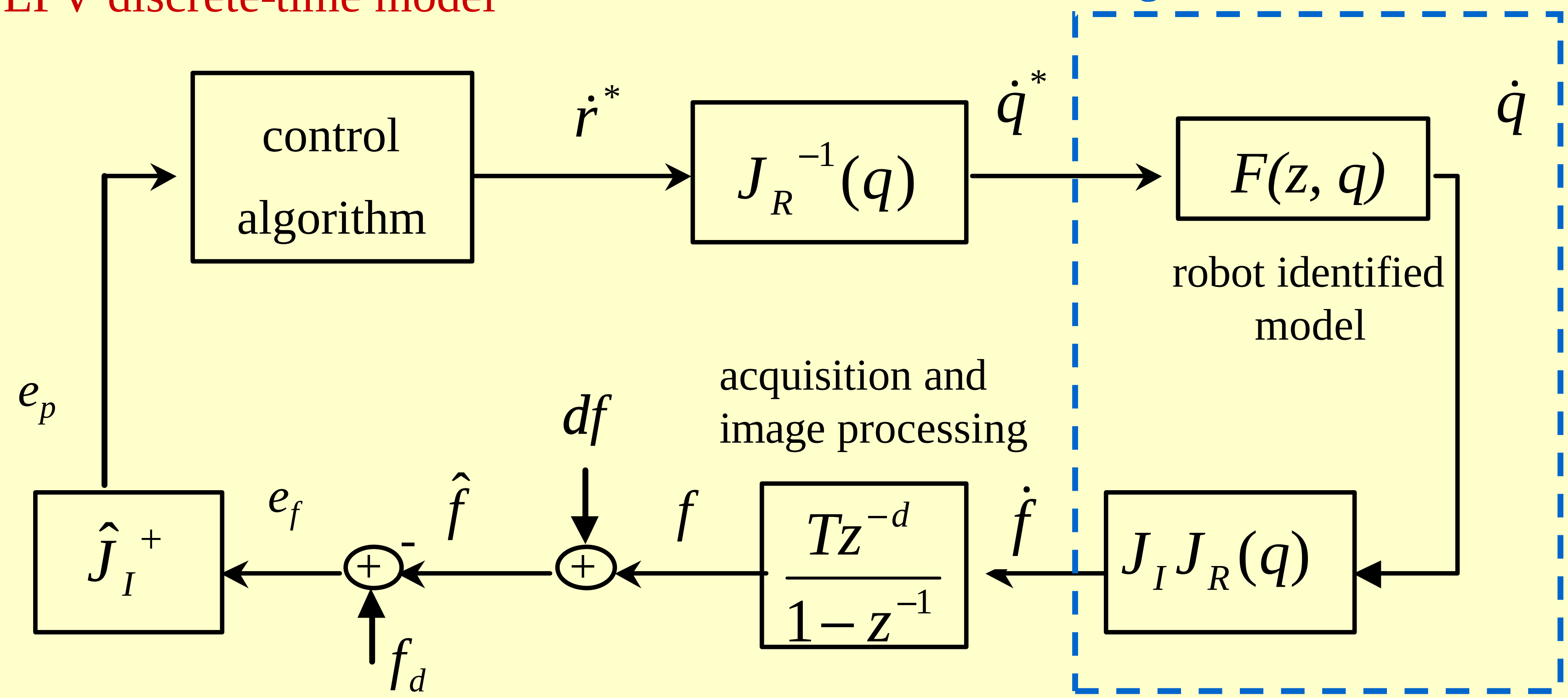
B. Stability and robustness (2)

LPV discrete-time model



GPC of a 6DOF robot vision loop :

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B. Stability and robustness (3)

- High bandwidth vision loop :
  - Non linear approach : rigid link robot manipulator model

$$t = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + f_r(q,\dot{q})$$

PD control scheme : *(R. Kelly, IEEE Trans. Rob. Aut., vol 12, 1996)*

$$t^* = g(q) - K_v\dot{q} - J_R{}^T(q)K_p\hat{J}_I{}^T e_f$$

Stability is proved only for a 2 DOF robot with no friction

=> Previous restrictions apply

Bibliography

- Hager, G. and S. Hutchinson. Special issue on vision-based control of robot manipulators. *IEEE Trans. Rob. Autom.*, vol 12, no 5, 1996.
- Corke, P. *Visual control of robots*. Research studies Press Ltd., Somerset, UK, 1996.

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