Visual servoing of a laparoscopic surgical robot

European Summer University

Medical Robotics

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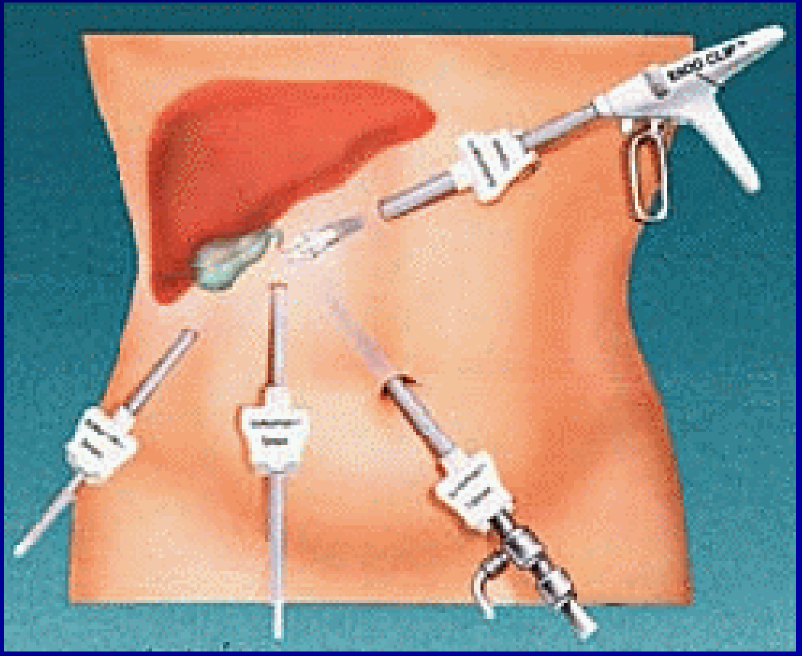
- Laparoscopic surgery :
  - Small incision points (trocart)
  - Endoscopic vision system



- Advantages :
  - Shorter recovery time
  - Lower infection risk
  - Smaller costs

- Difficulties :
  - Tiring gestures
  - Indirect visual feedback, lack of depth information
  - Inverted motions limited to 4 DOF
  - Poor haptic feedback

- Commercial systems to move the endoscope

  – AESOP (Computer Motion/Intuitive Surgical)

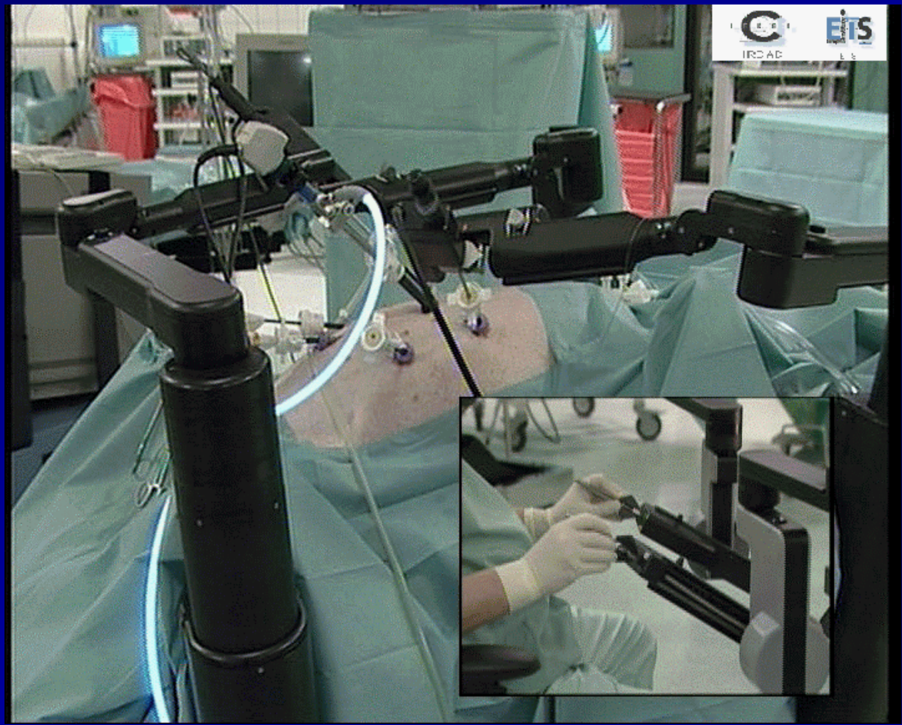
  – EndoAssist (Armstrong-Healthcare)

Voice controlled

Controlled with head motions

"The surgeon's third hand"

- Commercial robots to move the instruments
  - ZEUS (Computer Motion/Intuitive Surgical)



– Da Vinci (Intuitive Surgical)

- Advantages :
  - Confort for the surgeon
  - Increased precision
    - Demultiplication ratio – increased dexterity – filtering
  - Remove the holder of the endoscopic camera
  - Long distance surgery
- Difficulties :
  - Keep track of the instruments
  - Risk of contacts with the organs
  - Longer duration of surgical procedures

2.1- Instrument guidance

- Goal : surgical instrument guidance
  - Autonomous retrieval of the instruments
    - Bring the instrument in the field of view
    - Centering of the instrument in the image
  - Automatic positionning
    - Put the instrument at a desired location
    - Provide depth informations

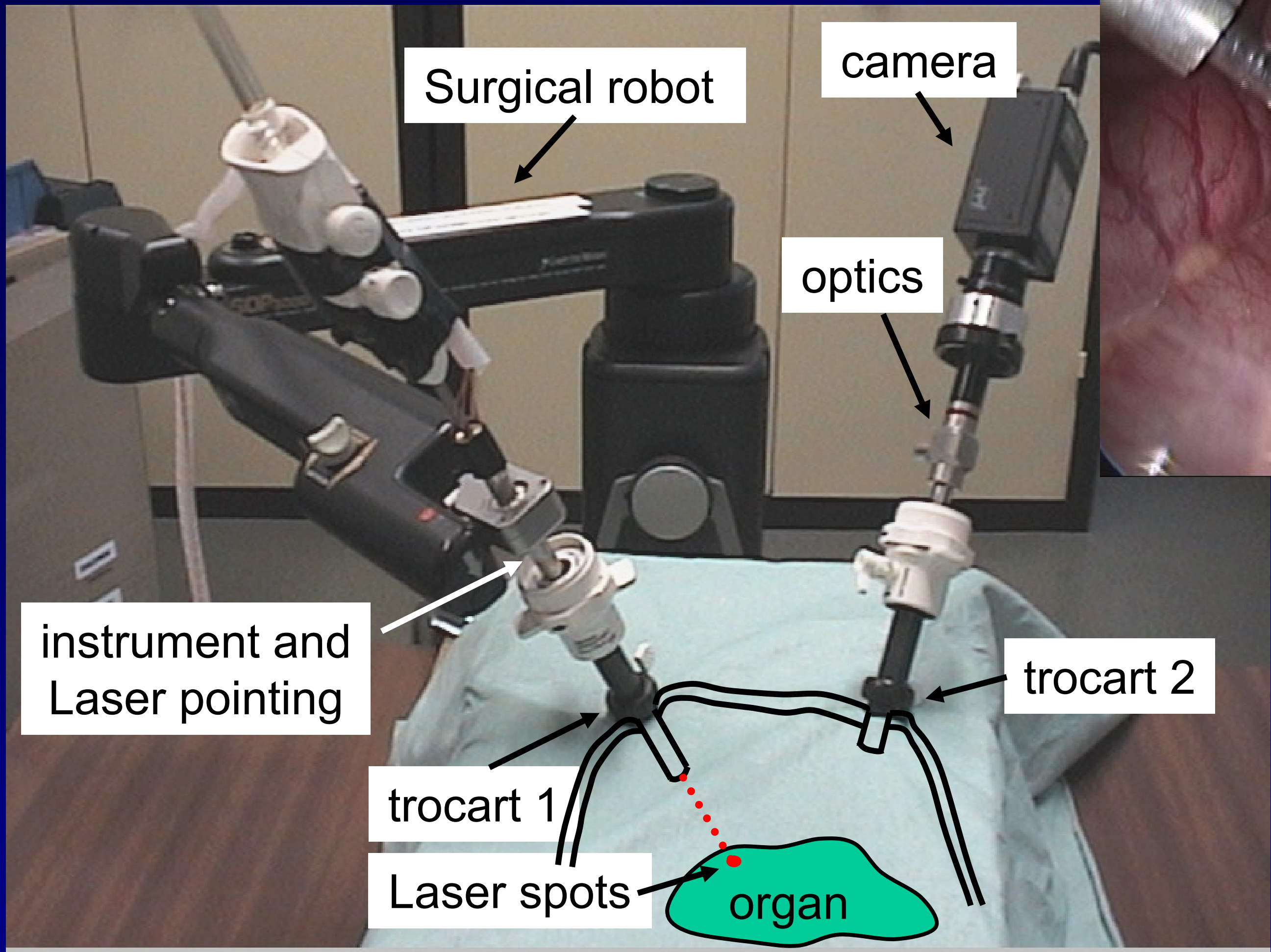
Motivations : - increase safety
- improve ergonomy
- speed up surgical procedures

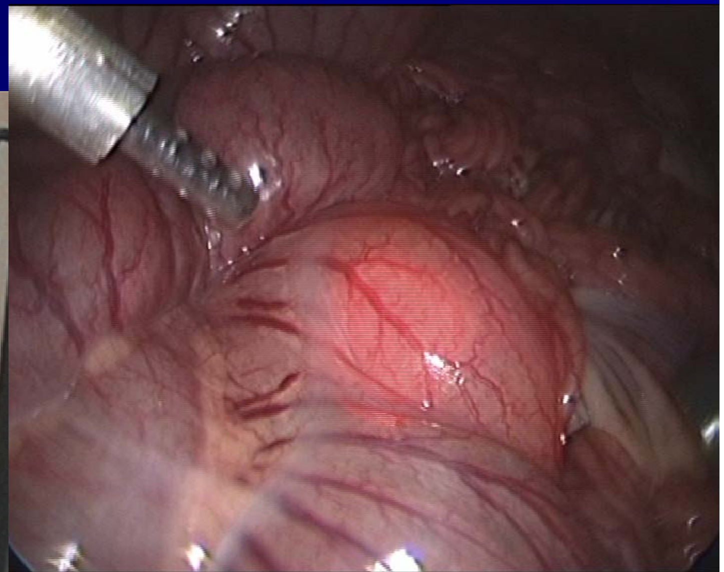
2.1- Instrument guidance

- Problems to solve
  - Localization of the instruments
    - Add structured information to the scene
    - Robust detection of visual informations
    - Depth estimation
  - Control of the robot using visual servoing
    - Find the relationship between motions in the image and control of the robotic arm with an external view
  - Maximum safety
    - No uncontrolled contacts with soft tissues
    - Procedures in case of loss of visual features

2.2- Description of the experimental setup

- Robotic system





Laser projection
to add information
to the scene

External camera
configuration

2.2- Description of the experimental setup

- Laser pointing device



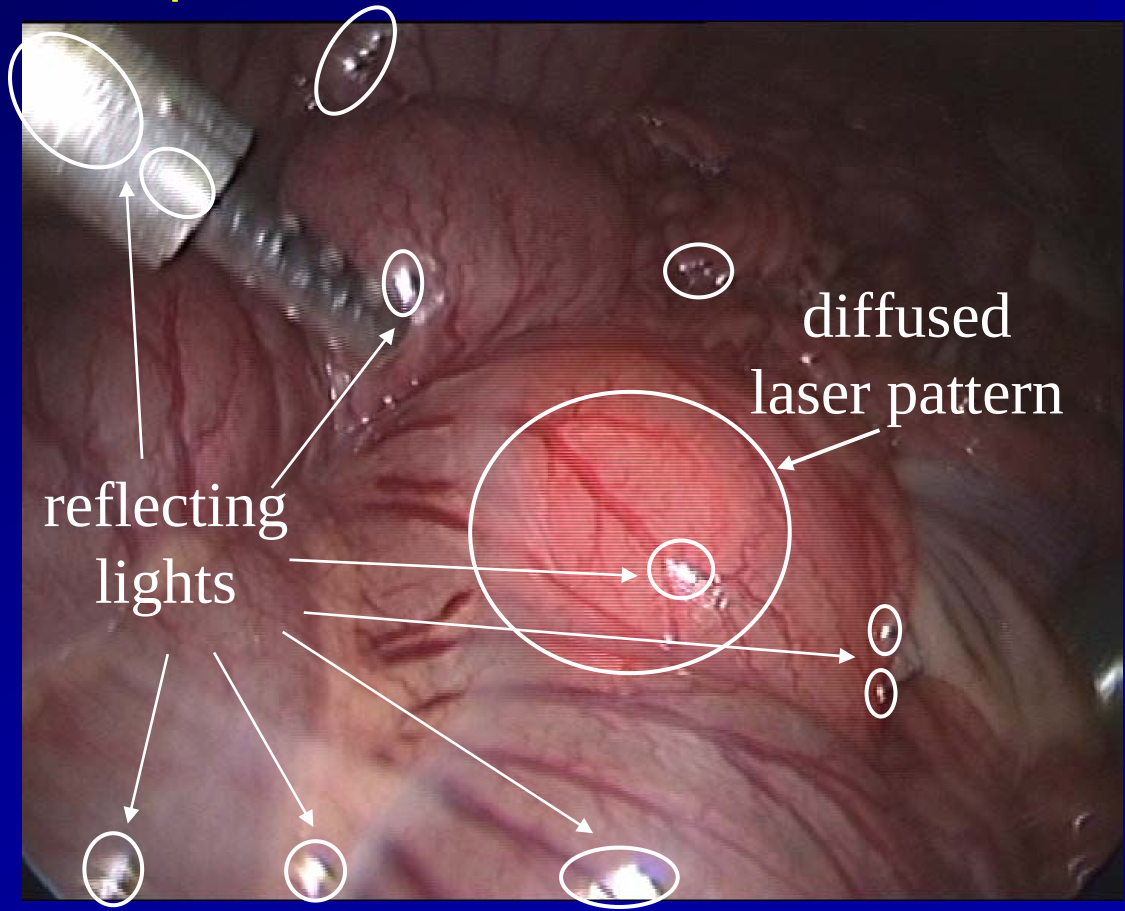
  - 4 laser spots (redundancy factor)
  - To be used with standard instruments (4 mm)
  - Using standard trocart (10 mm)

- 3 optical markers (detection of the instrument)

3.1- Difficulties

- Goal: to obtain the image coordinates
  - Center of laser spots and optical markers

- Difficulties
  - Bright spots
  - Diffused laser spots
  - Breathing motions
  - Real-time processing



Blinking laser spots and optical markers

- Even frames : laser on – markers off
- Odd frames : markers on – laser off

laser

marqueur

ligne N°:																														
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
6	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
8	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
10	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Not a feature

- High-pass filtering

$*$

2	2	2	2	2
-4	-4	-4	-4	-4
4	4	4	4	4
-4	-4	-4	-4	-4
2	2	2	2	2

mask

$=$

ligne N°:																														
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
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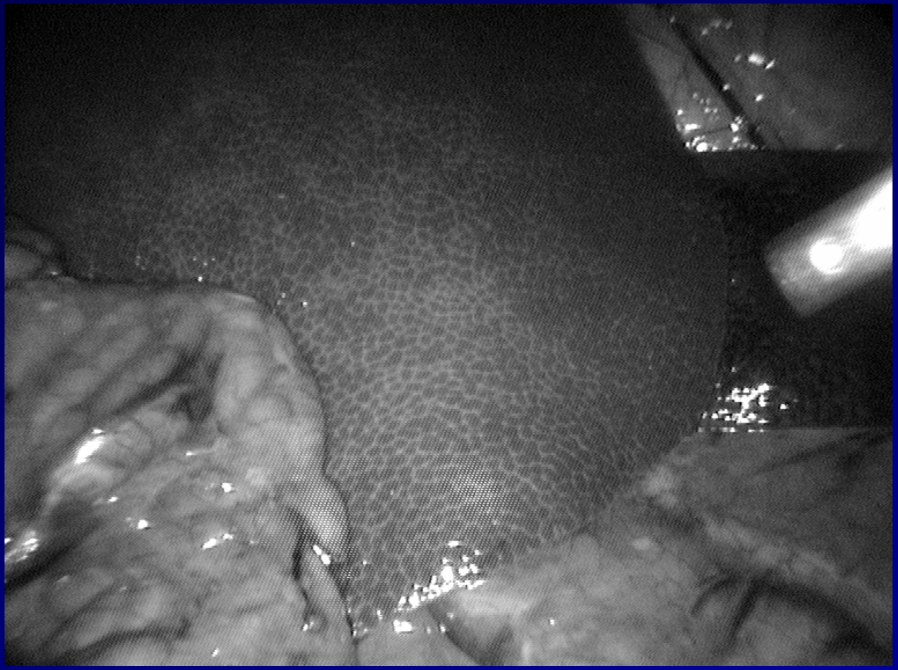
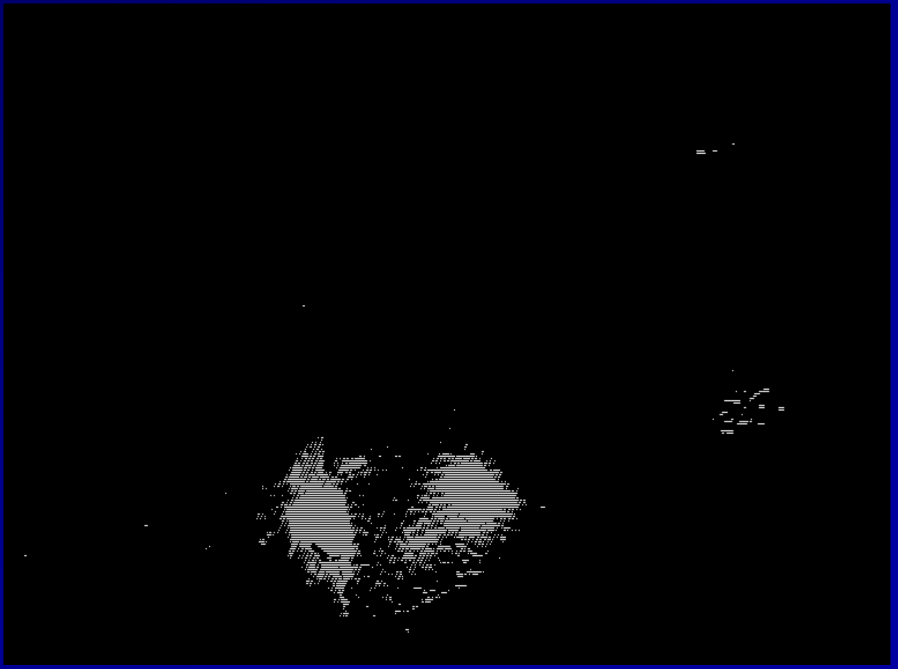
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

3.2- Robust detection

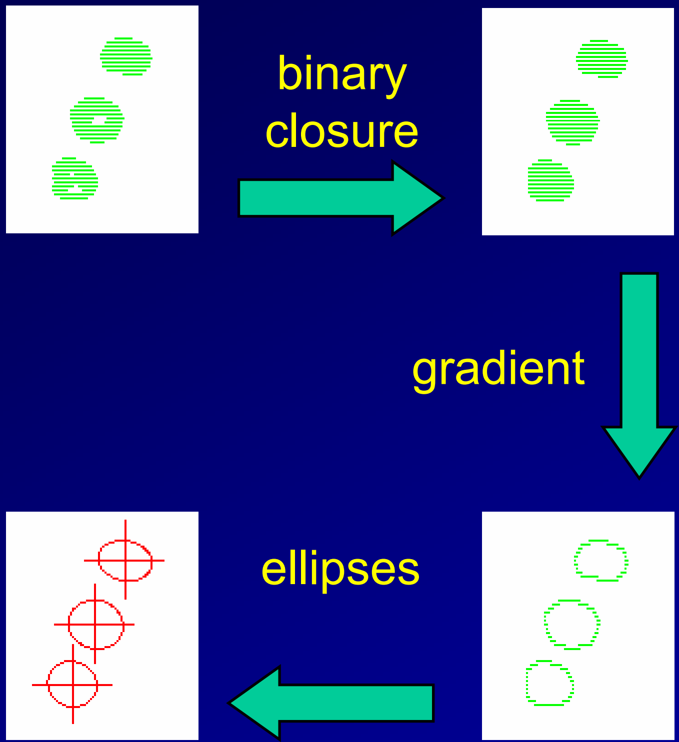
- Laser spots detection





3.3- Coordinates

- Laser spot center of mass : $\mathbf{s}_p = \begin{pmatrix} u_p & v_p \end{pmatrix}^T$
- Optical markers : ellipse detection



3.4- Depth measurement

- Depth measurement using a bi-ratio

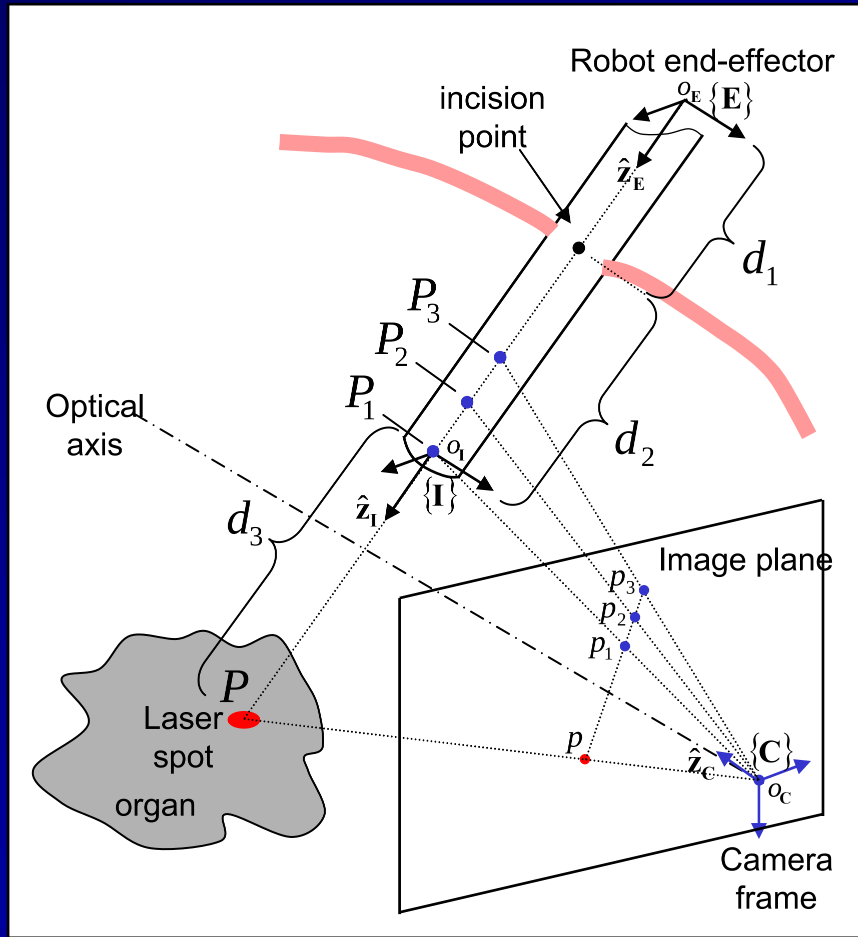
Colinear points P, P_1, P_2, P_3

projections p, p_1, p_2, p_3

Bi-ratio :

$$\tau = \frac{\left(\dfrac{\overline{pp_2}}{\overline{p_1p_2}}\right)}{\left(\dfrac{\overline{pp_3}}{\overline{p_1p_3}}\right)} = \frac{\left(\dfrac{\overline{PP_2}}{\overline{P_1P_2}}\right)}{\left(\dfrac{\overline{PP_3}}{\overline{P_1P_3}}\right)}$$

$$d_3 = \overline{PP_1} = (\tau - 1)\frac{\overline{P_1P_2}.\overline{P_1P_3}}{\overline{P_1P_3} - \tau.\overline{P_1P_2}}$$

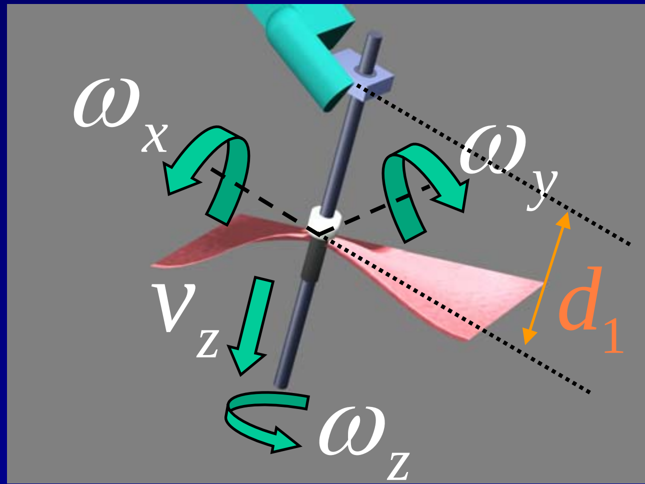


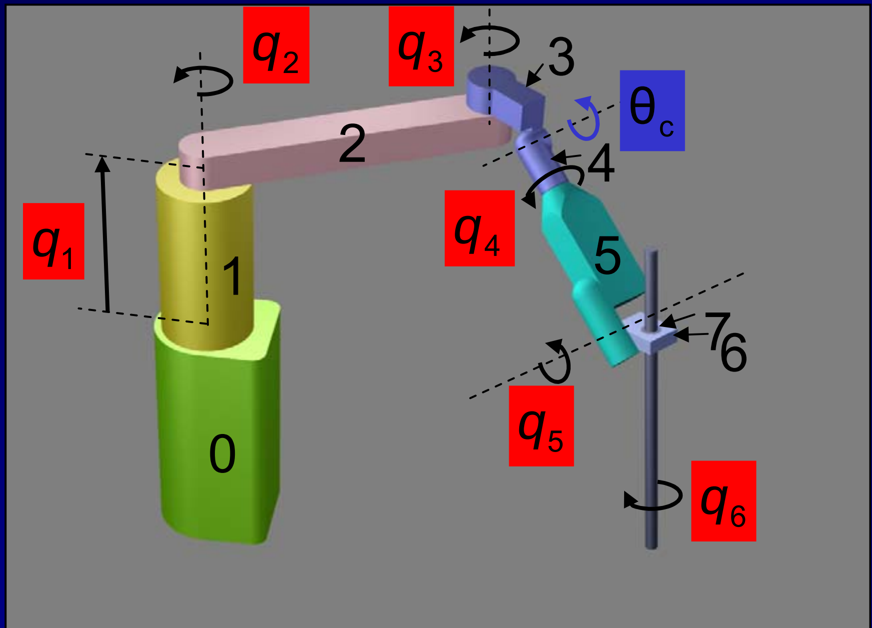
- Kinematics in laparoscopic surgery

  -constraints: 4 DOF

$$\dot{\mathbf{W}}_{op} = \begin{pmatrix} \omega_x & \omega_y & \omega_z & v_z \end{pmatrix}^{\mathrm{T}}$$

  -AESOP: 6 DOF (2 passive joints)





– kinematic model :

$$\dot{\mathbf{W}}_{op} = \mathbf{J}_{op}(\mathbf{q}, d_1)\dot{\mathbf{q}}_c$$

$$\dot{\mathbf{q}}_c^* = \mathbf{J}_{op}(\mathbf{q}, \hat{d}_1)^{-1}\dot{\mathbf{W}}_{op}^*$$

- Estimation of d_1 distance using measurements of O_E

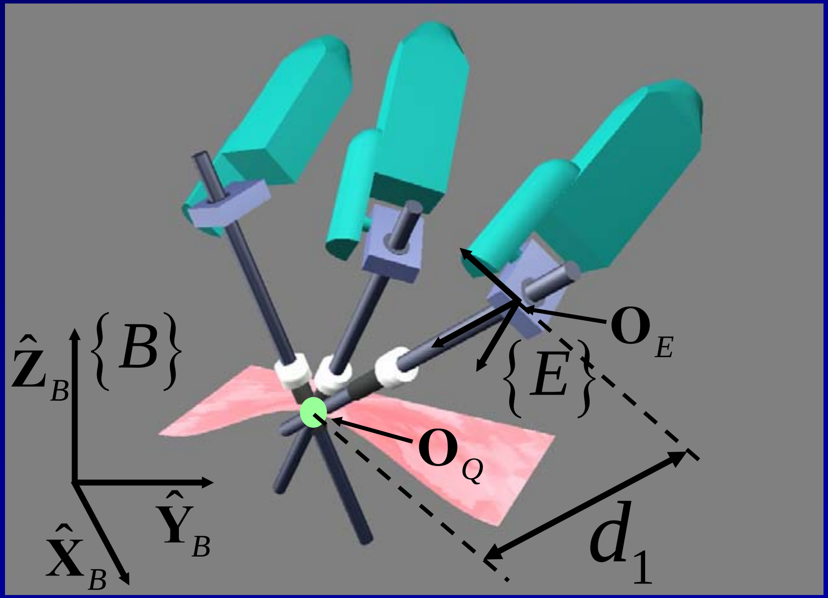
  - slow variations of incision point

  $\mathbf{O}_Q$ = intersection of successive instrument axis

  $\Rightarrow$ Estimation : $\mathbf{O}_Q$ recursive least-squares

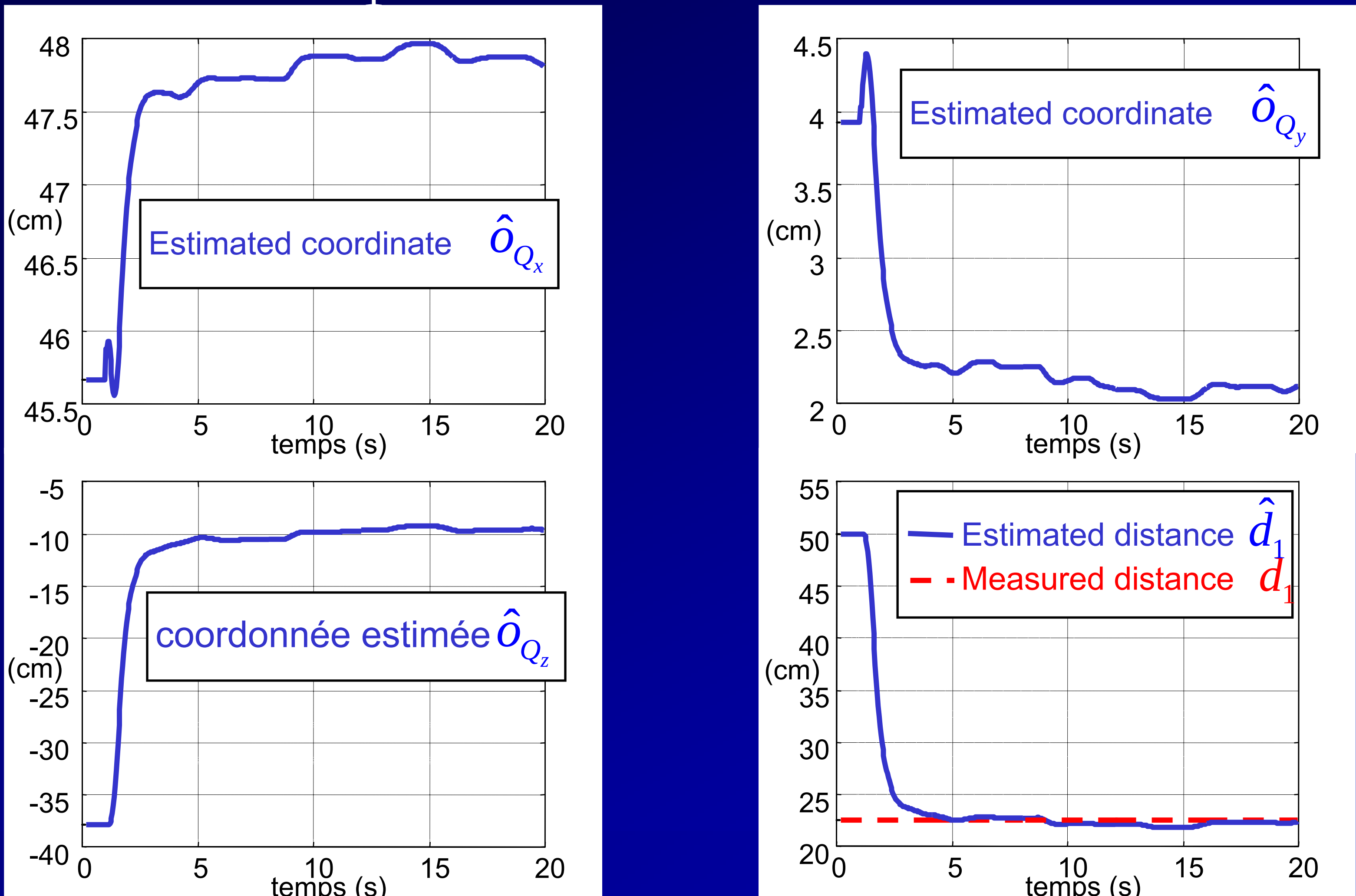
  with: • forgetting factor
  • dead zone

$$\hat{d}_1 = \overline{\hat{\mathbf{O}}_Q \mathbf{O}_E}$$

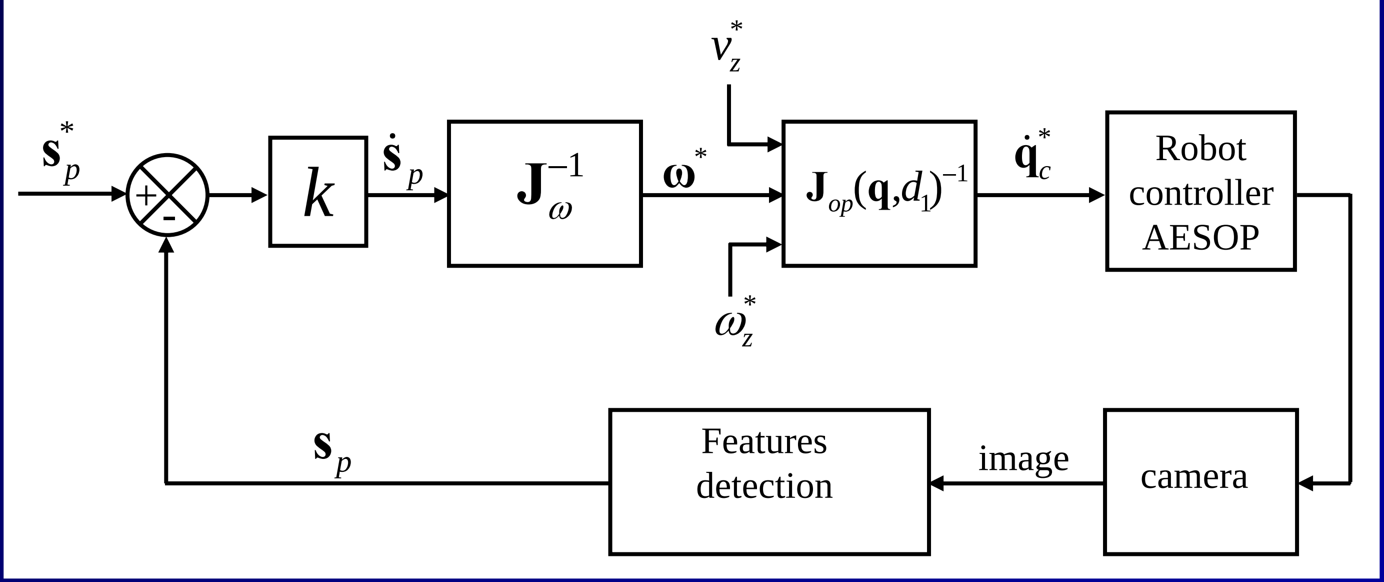


4.1- Kinematics

- Estimation of d_1 distance



- 2D direct visual servoing scheme (Image-based)



- controlled variable : $\mathbf{S}_p = \begin{pmatrix} u_p & v_p \end{pmatrix}^T$
- control input : $\boldsymbol{\omega}^* = \begin{pmatrix} \omega_x^* & \omega_y^* \end{pmatrix}^T$
- control law : $\dot{\mathbf{S}}_p = k\left(\mathbf{S}_p^* - \mathbf{S}_p\right) = \mathbf{J}_\omega \boldsymbol{\omega}^*$

with :
- positive gain : k
  exponentially decreasing
- interaction matrix $\mathbf{J}_\omega$

4.3- Estimation of interaction matrix

- Open loop estimation of $\mathbf{J}_\omega$

  – Hypothesis : standstill camera $\hat{\mathbf{J}}_\omega = \begin{bmatrix} \hat{J}_{\omega 11} & \hat{J}_{\omega 12} \\ \hat{J}_{\omega 21} & \hat{J}_{\omega 22} \end{bmatrix}$

$$\Delta T \quad \begin{cases} \omega_x^* = cst \\ \omega_y^* = 0 \end{cases} \Rightarrow \quad \hat{J}_{\omega 11} = \frac{\Delta u_p}{\omega_x^* \Delta T} \qquad \hat{J}_{\omega 21} = \frac{\Delta v_p}{\omega_x^* \Delta T}$$

$$\Delta T \quad \begin{cases} \omega_x^* = 0 \\ \omega_y^* = cst \end{cases} \Rightarrow \quad \hat{J}_{\omega 12} = \frac{\Delta u_p}{\omega_y^* \Delta T} \qquad \hat{J}_{\omega 22} = \frac{\Delta v_p}{\omega_y^* \Delta T}$$

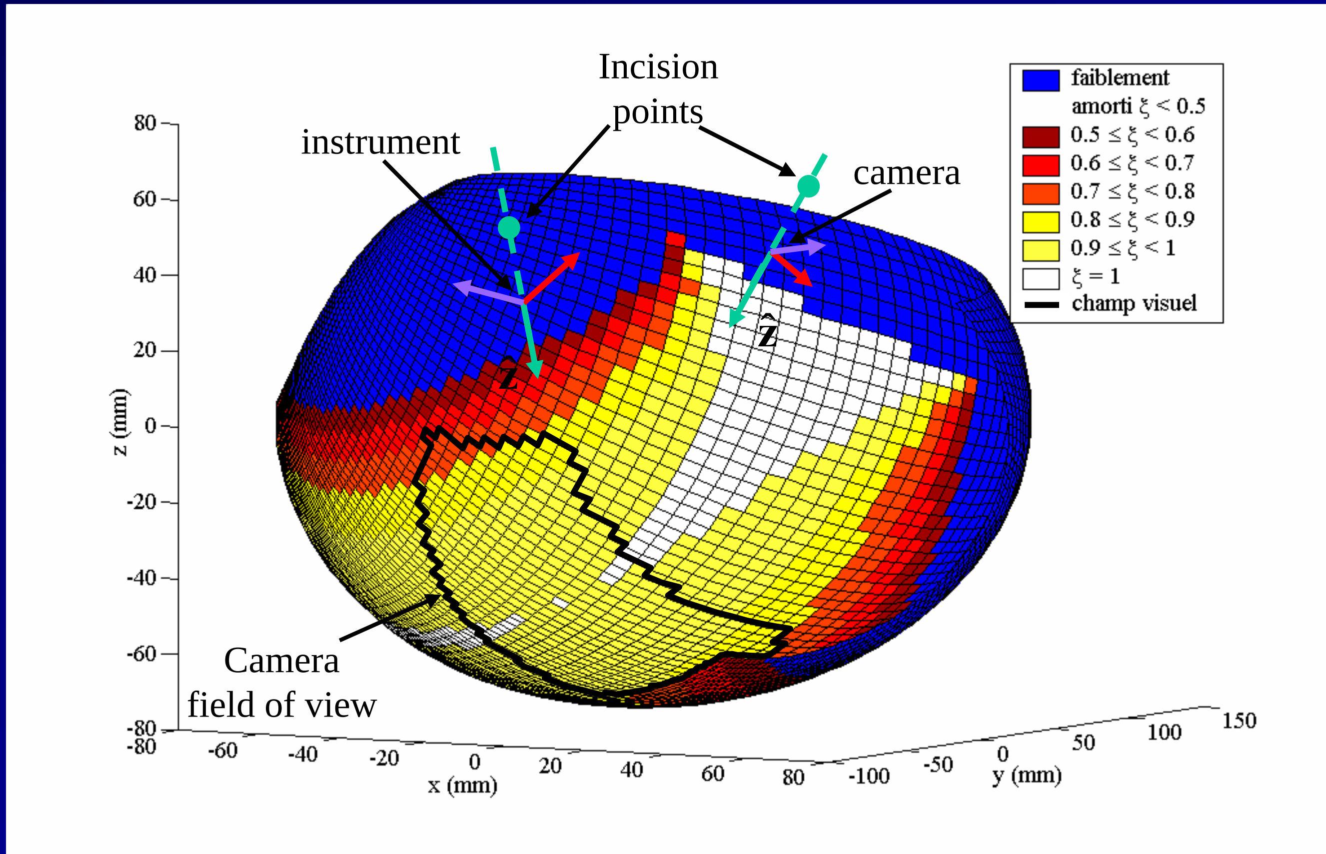
  – Stability if $\quad \mathbf{J}_\omega \hat{\mathbf{J}}_\omega^{-1} > \mathbf{0}$

4.3- Estimation of interaction matrix

- Stability study

- robot = integrator
  1/s

- poles S_1, S_2
  = eigen values of
  $\mathbf{A} = -k\mathbf{J}_{\omega}\hat{\mathbf{J}}_{\omega}^{-1}$

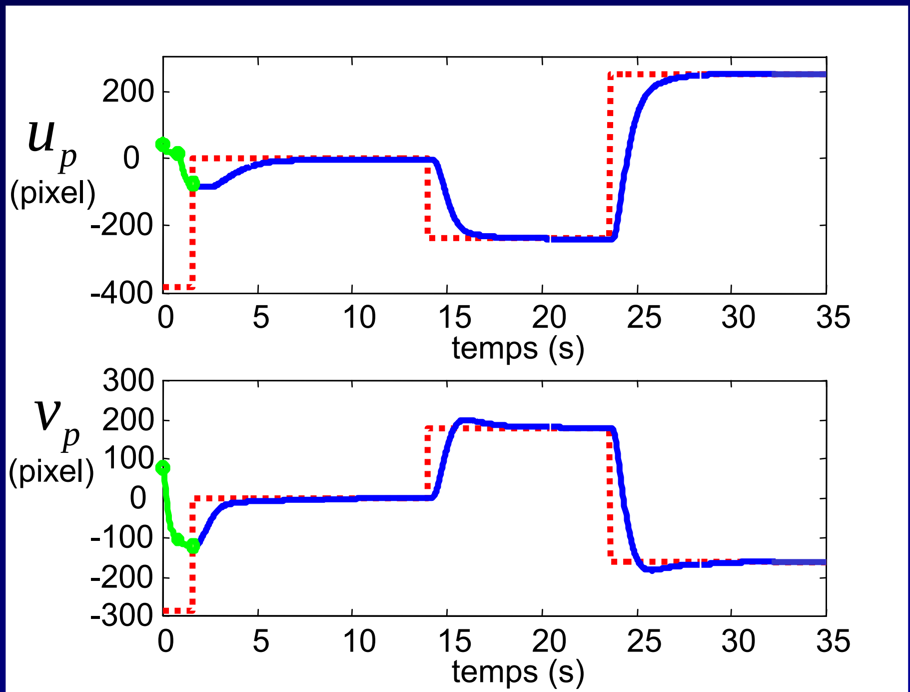


damping factor ζ

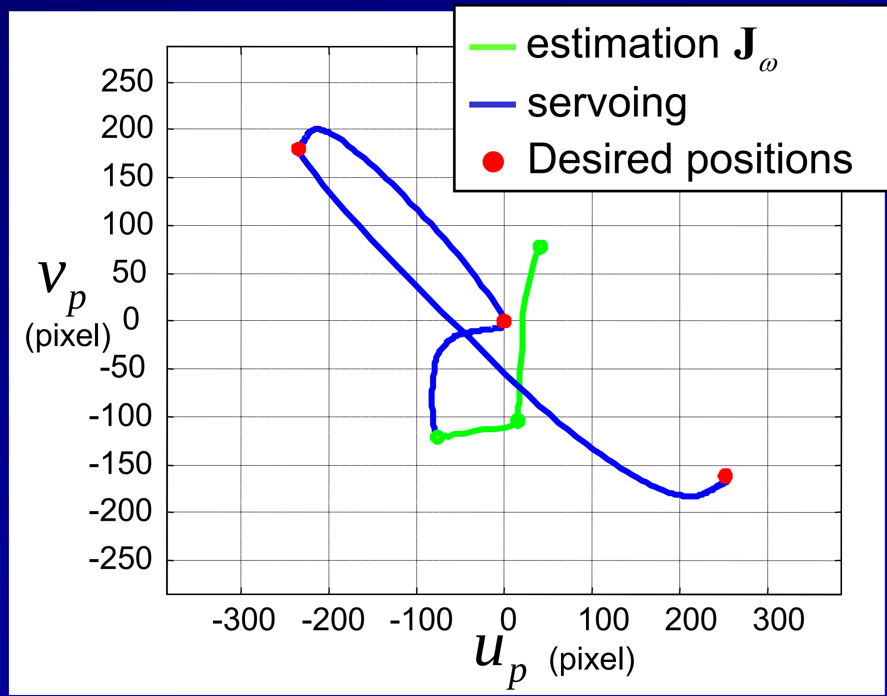
4.3- Estimation of interaction matrix

- Experimental results (on laboratory equipment)

u_p, v_p



Trajectory in the image



5.1- Instrument retrieval

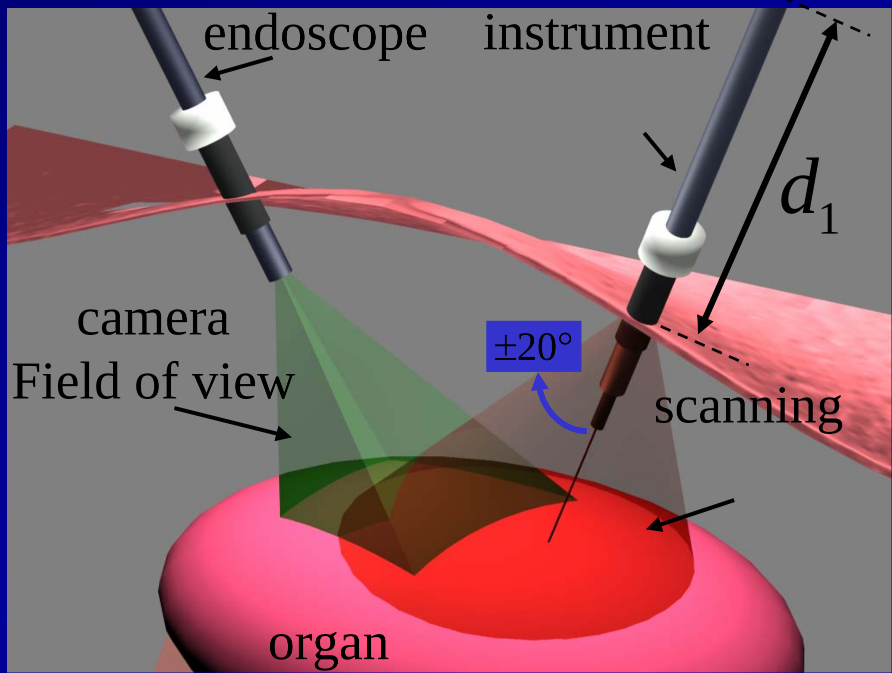
- Steps :

1. Instrument out (safety) (EX)
   - Servoing of d_1 distance to a reference d_1^*

     control of v_z^*

2. Scanning (BA)
   - Open loop trajectory

     of ω_x^*, ω_y^*



3. Laser spot centering (CE)

- Interaction matrix identification $\mathbf{J}_{\omega}$
- 2D visual servoing
  - Control of ω_x^*, ω_y^*

4. Instrument in (IN)

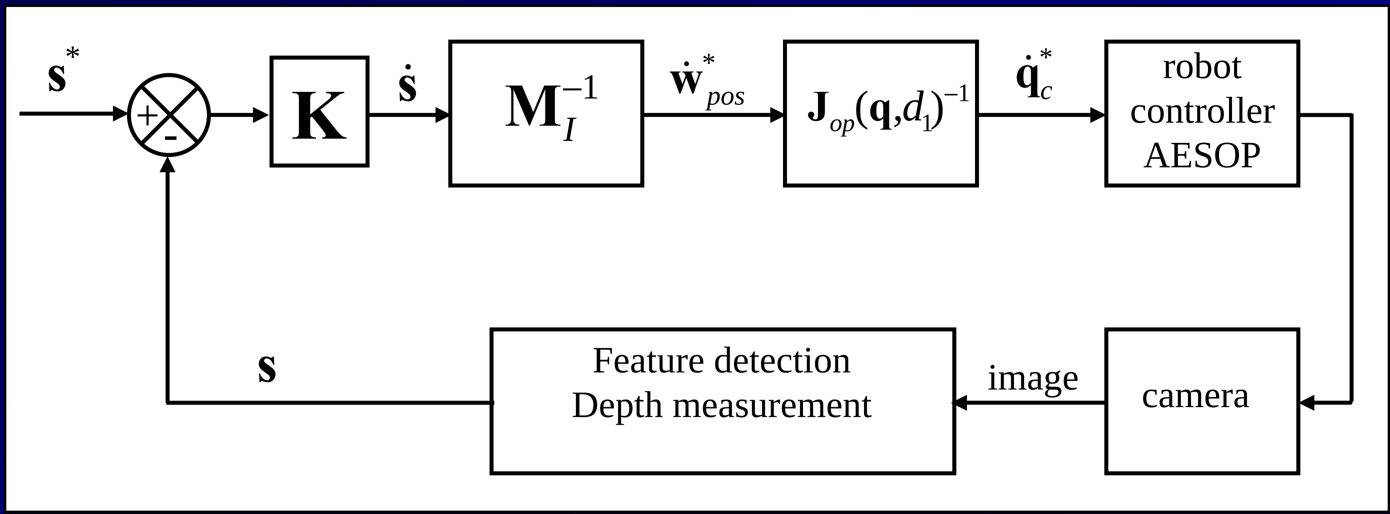
- Open loop until optical markers are visible: $v_z^* = cst$

- 2D visual servoing maintained

5.1- Instrument retrieval

5.2- 3D positioning of the instrument

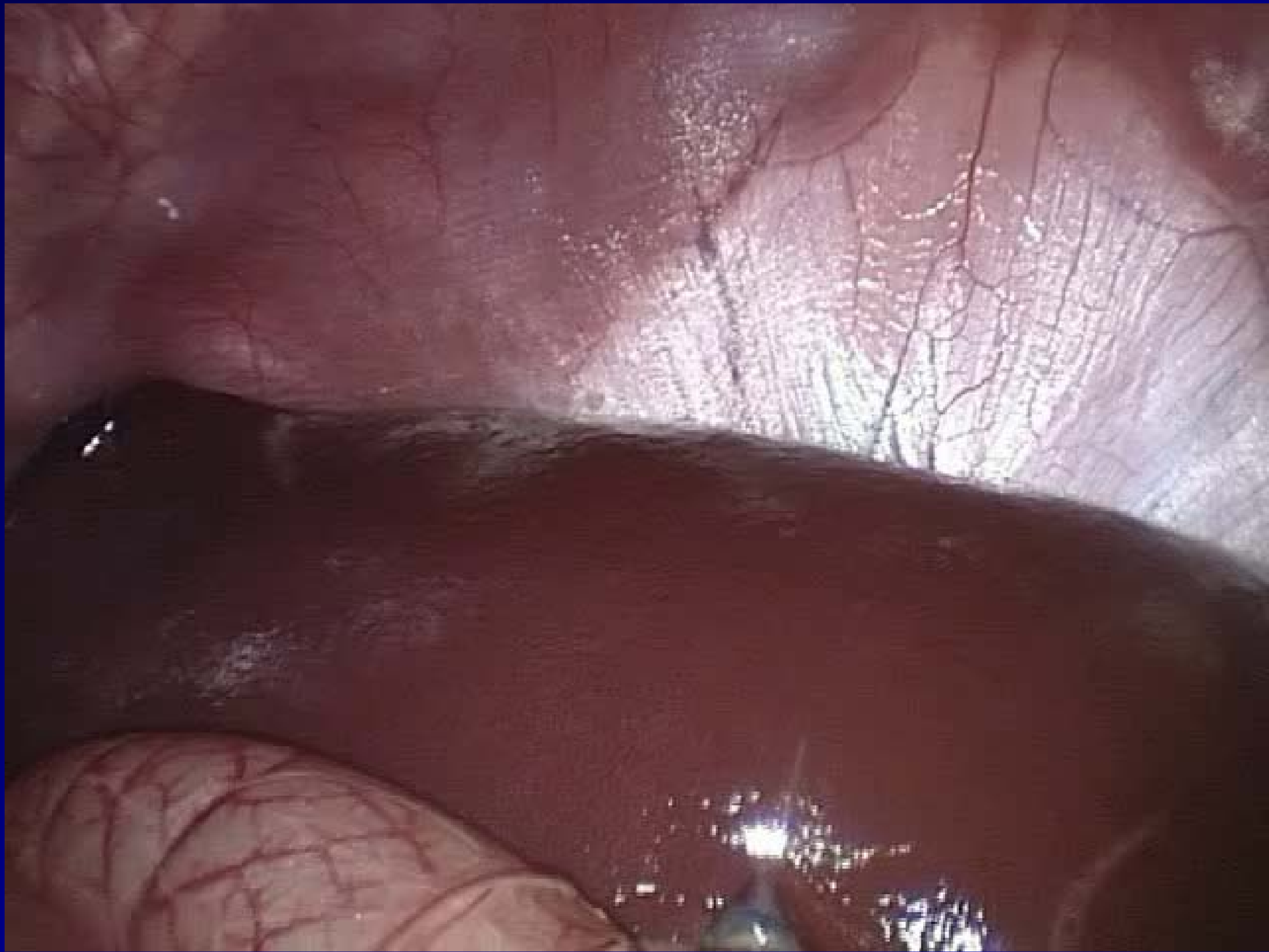
- Hybrid visual servoing : $\mathbf{s} = \begin{bmatrix} u_p & v_p & d_3 \end{bmatrix}^T$



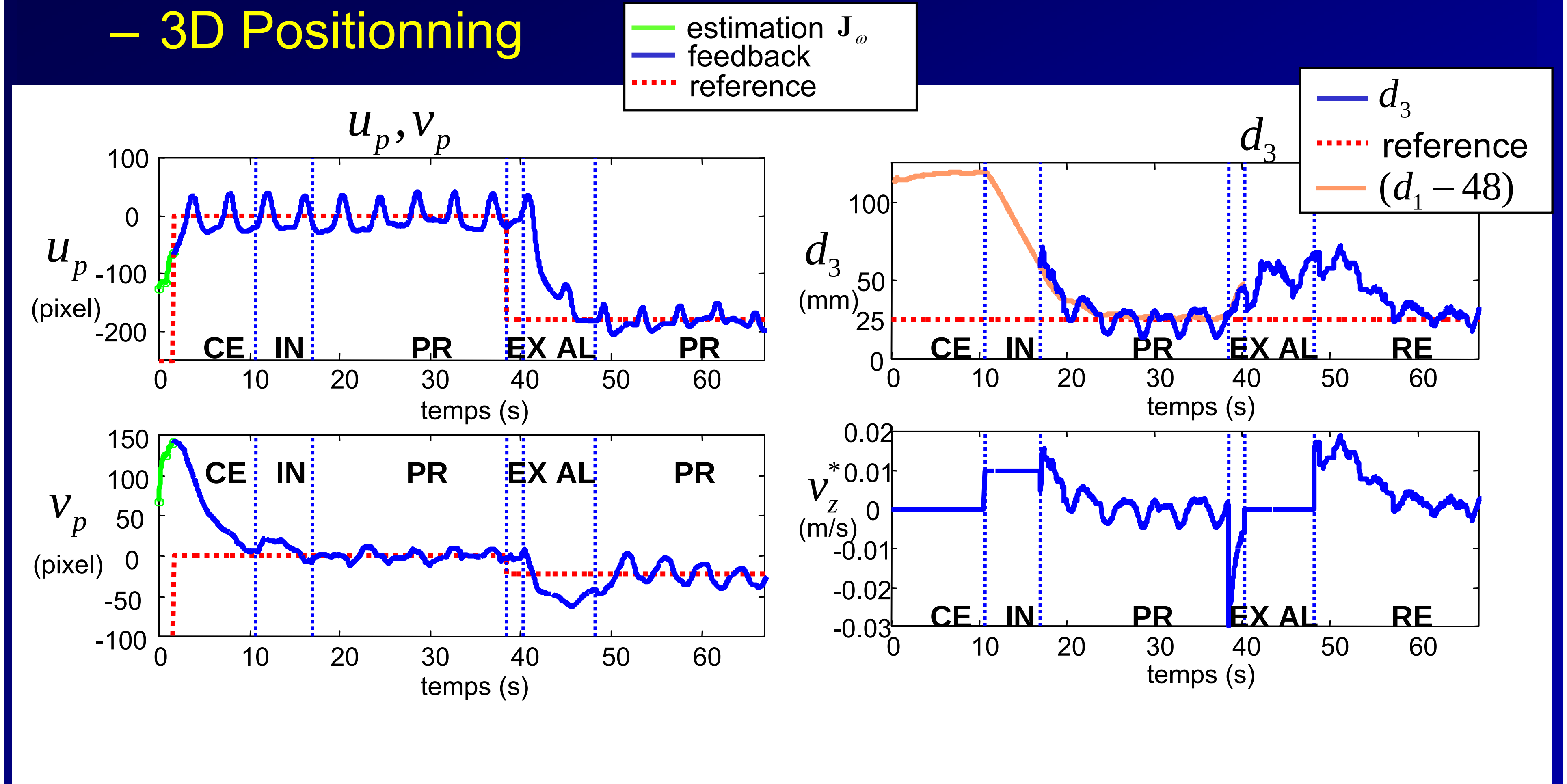
Control law : $$\begin{bmatrix} \omega_x^* & \omega_y^* & v_z^* \end{bmatrix}^T = \mathbf{M}_I^{-1}\mathbf{K}\left(\mathbf{s}^* - \mathbf{s}\right)$$

with $$\mathbf{M}_I = \begin{bmatrix} \hat{\mathbf{J}}_\omega & \mathbf{0}_{[2\times1]} \\ \mathbf{0}_{[1\times2]} & -1 \end{bmatrix} \qquad \mathbf{K} = \begin{bmatrix} k\mathbf{I}_{[2\times2]} & 0 \\ 0 & k_d \end{bmatrix}$$

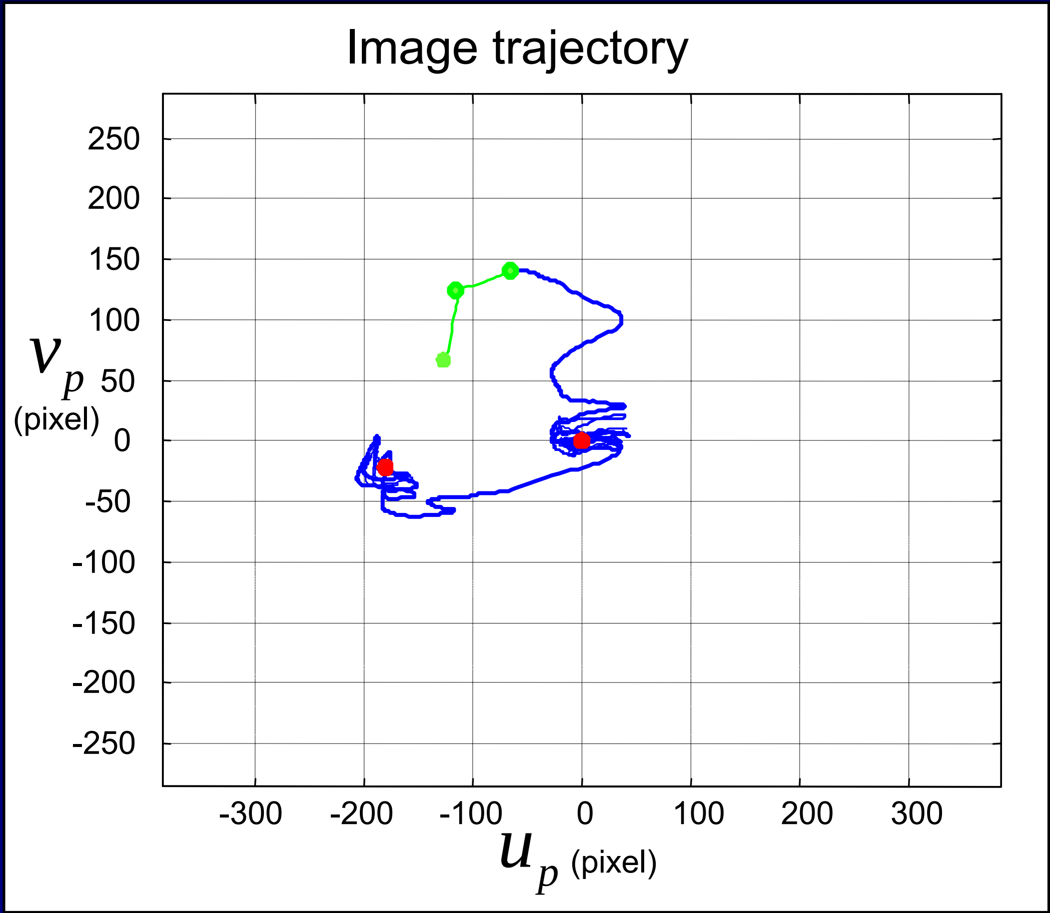
5.2- 3D positioning of the instrument



- Experimental results (in vivo)
  - 3D Positionning



- Experimental results (in vivo)



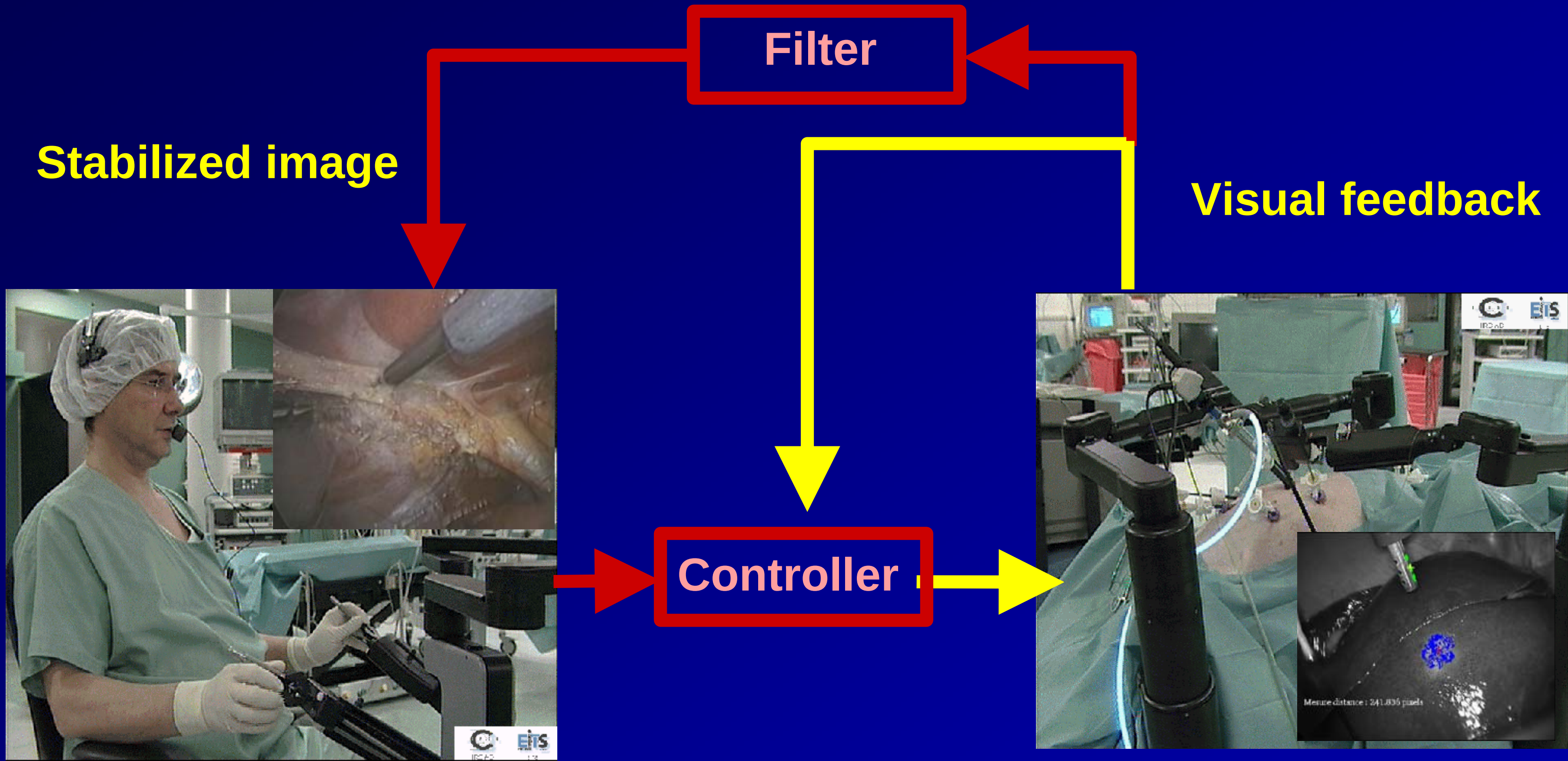
- Periodic disturbance induced by breathing

- Error reduction
$\Rightarrow \uparrow$ gains k and k_d

- Problem : AESOP controller
Too slow (time delay 160 ms)

- Solutions :
  - predictive model
  - faster robot

6- Organ motion compensation
6.1- Proposed strategy

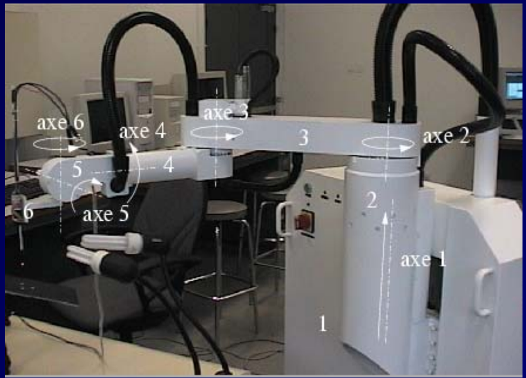


Predictive control law : take into account periodic disturbance

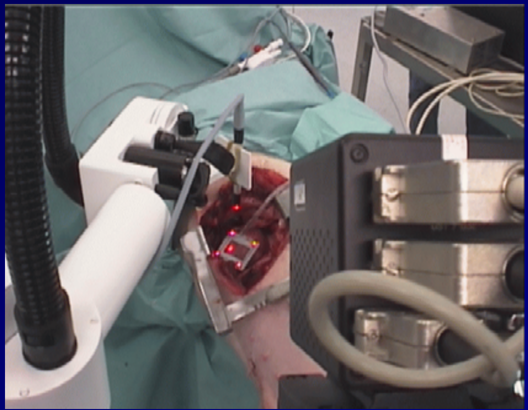
6.2- Breathing motion compensation

Predictive control law

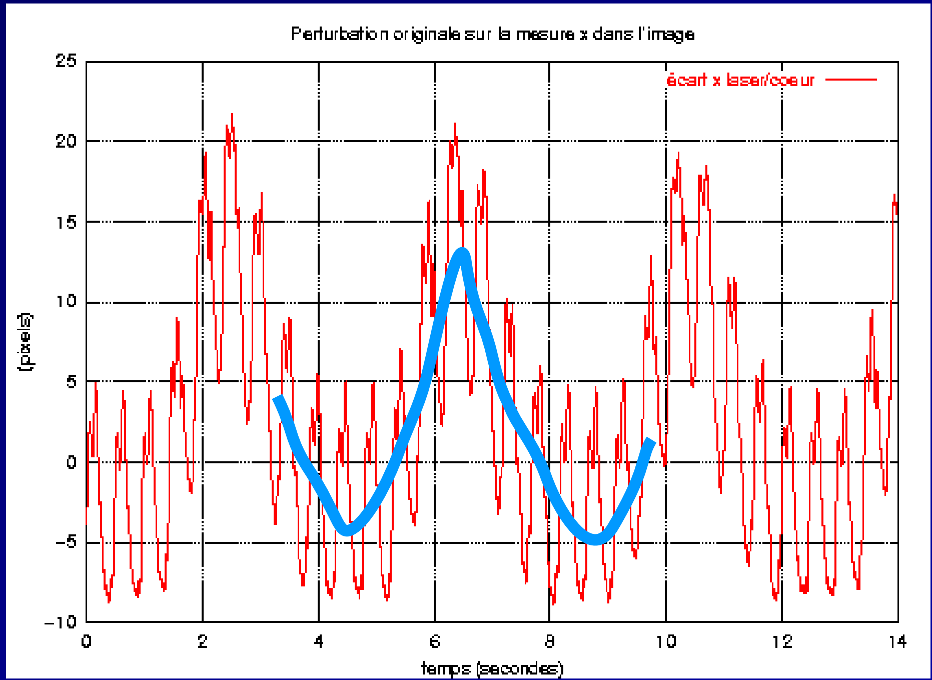
6.3- Beating heart motion compensation



Fast robot



Fast camera (500hz)



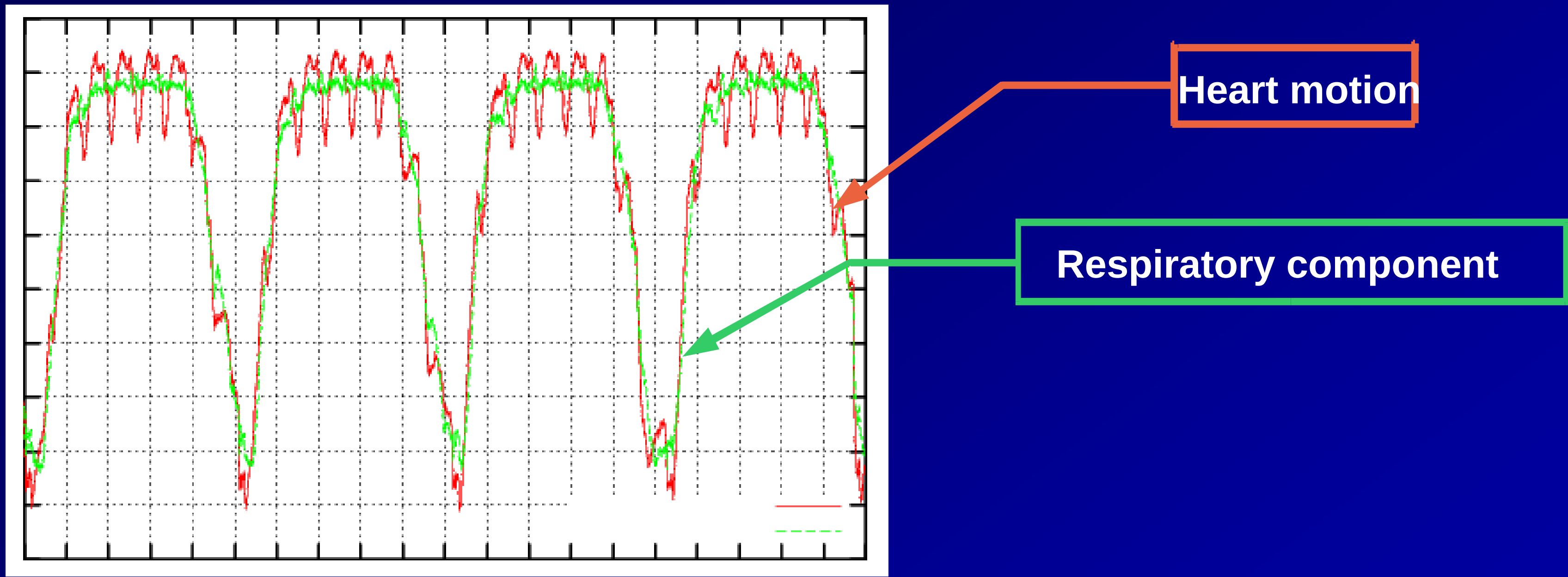
2 types of motion: - slow (~0.25 Hz)
- fast (~1.5 Hz)

In vivo experiments

Predictive control law

6- Organ motion compensation

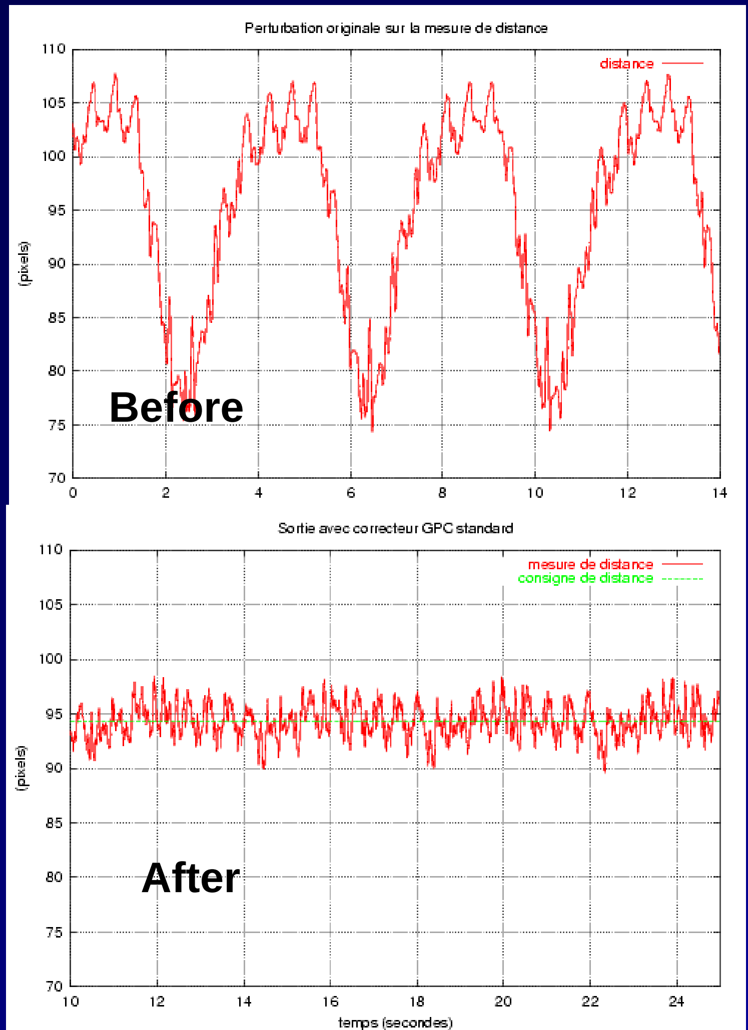
6.2- Beating heart motion compensation

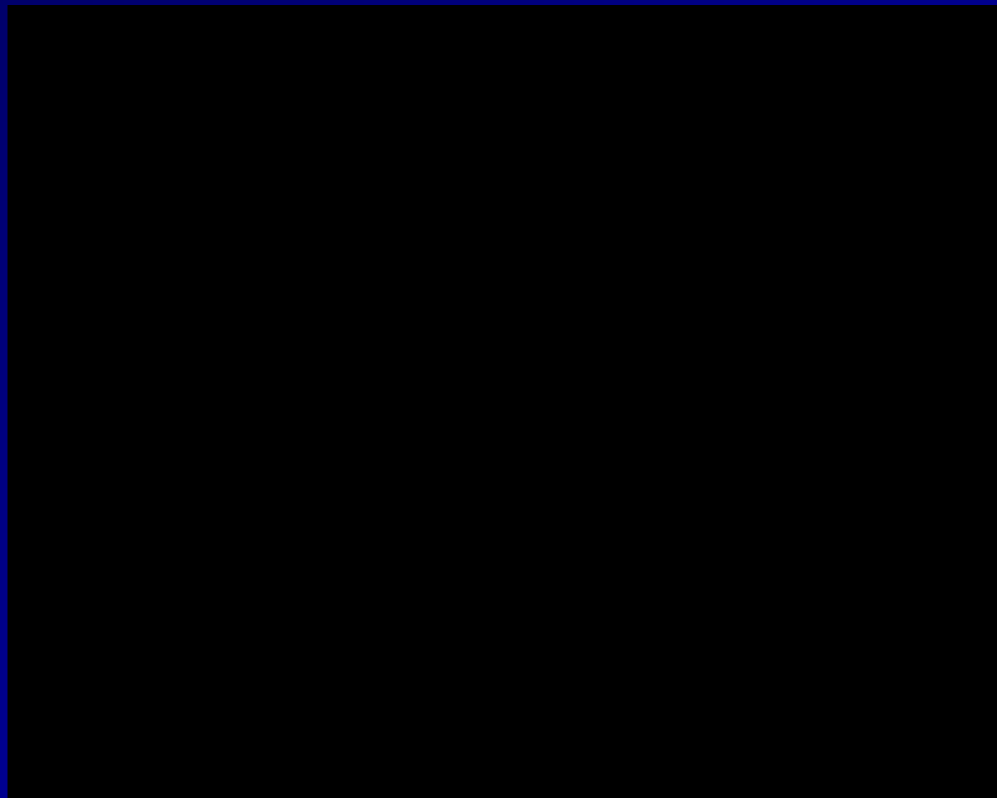


Adaptive filtering of 12 harmonics of the heart beat rate

6- Organ motion compensation

6.2- Beating heart motion compensation





In vivo results

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