Visual servoing for physiological motion compensation

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Outline of the presentation

1. Background on visual servoing
2. Visual servoing and medical robotics
3. Physiological motions
4. Predictive/repetitive control
5. Active robotic filtering
6. Future

1. Visual servoing
Introduction

Definition : ***position control of a mechanical device using real-time visual feedback***

Y. Shirai and H. Inoue, "Guiding a robot by visual feedback in assembling tasks", 1973

Hill and Parks, 1979 : use of a projected optical marker

1. Visual servoing
Introduction

Weiss, 1984 : image-based visual servoing

Espiau ***et al.***, 1992 : task-function approach

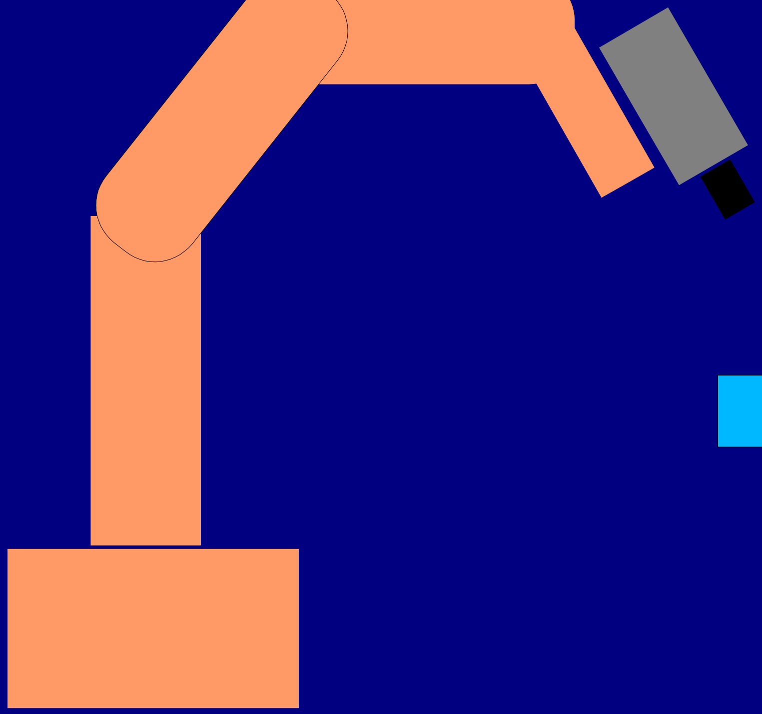
Corke, 1996 : dynamic effects

Malis ***et al.***, 1998 : 2D1/2 visual servoing

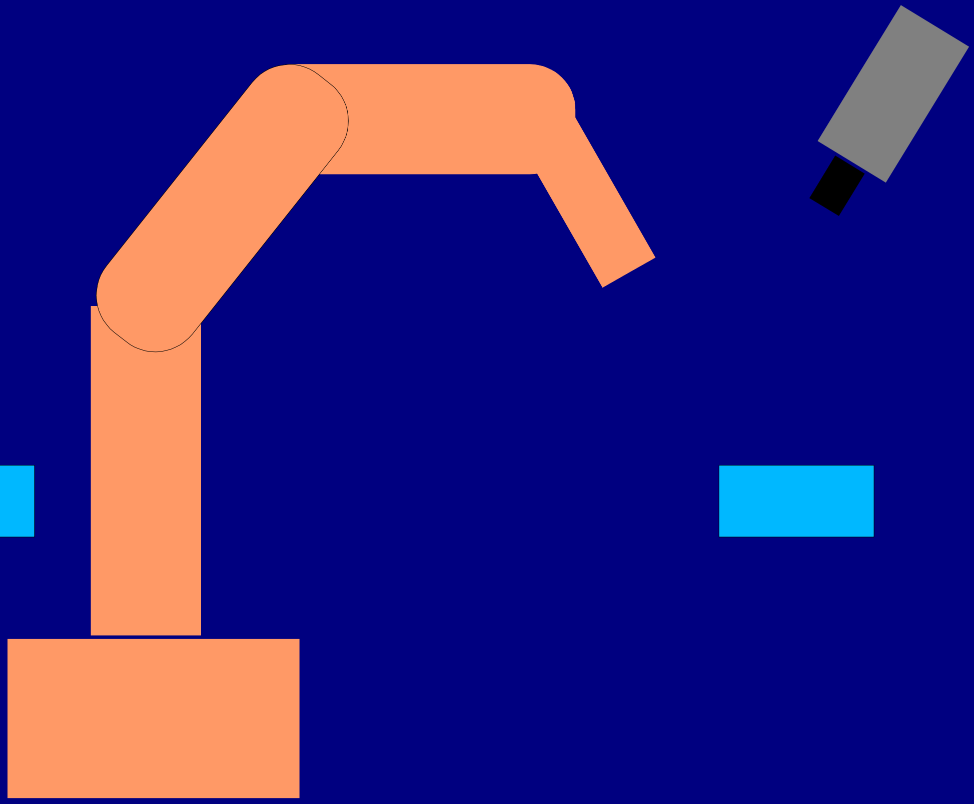
Nakabo ***et al.***, 1998 : 1000 Hz visual servoing

Nakamura ***et al.***, 2001 : heartbeat synchronization

1. Visual servoing
The visual sensor

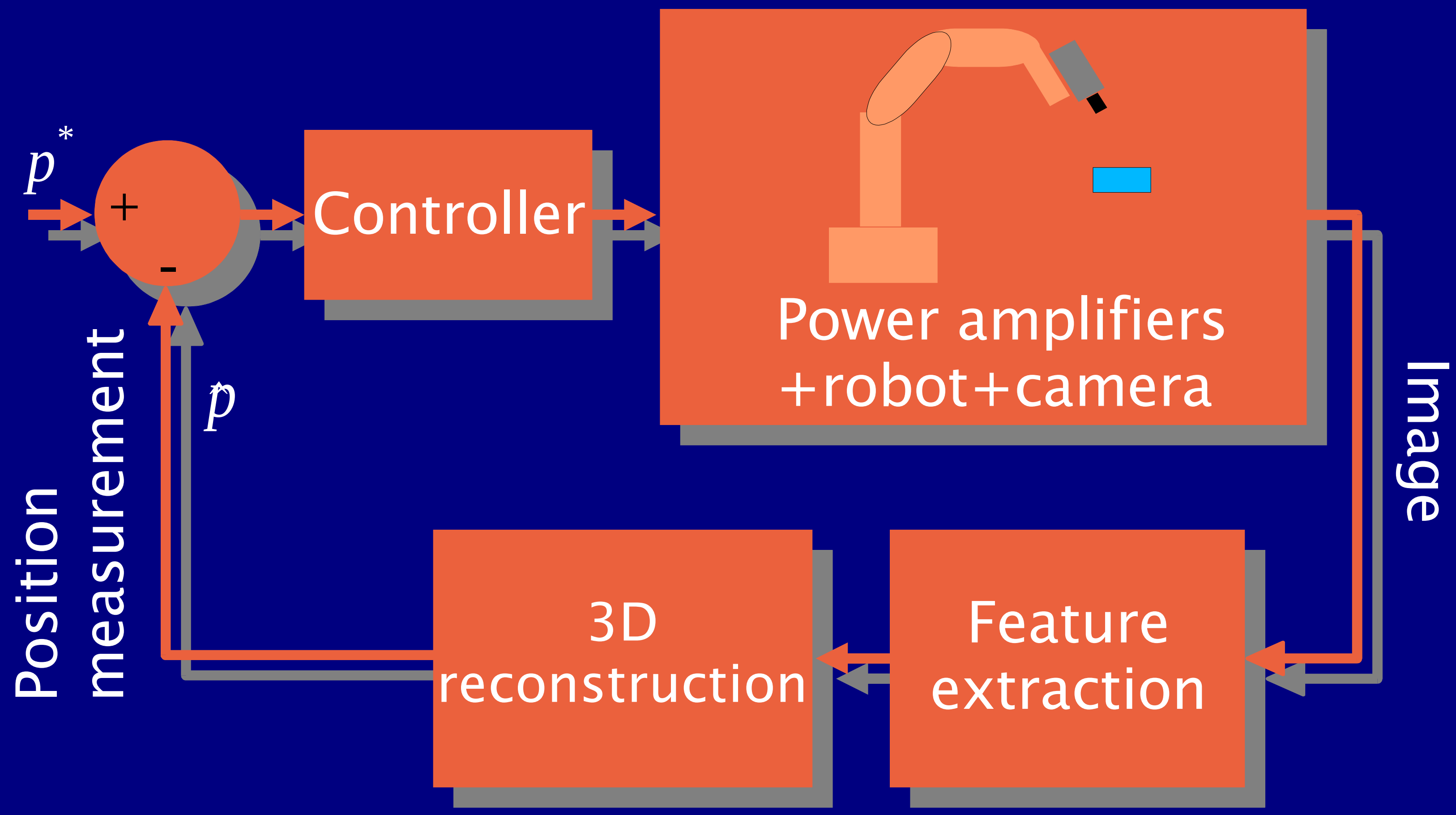


Eye in hand configuration

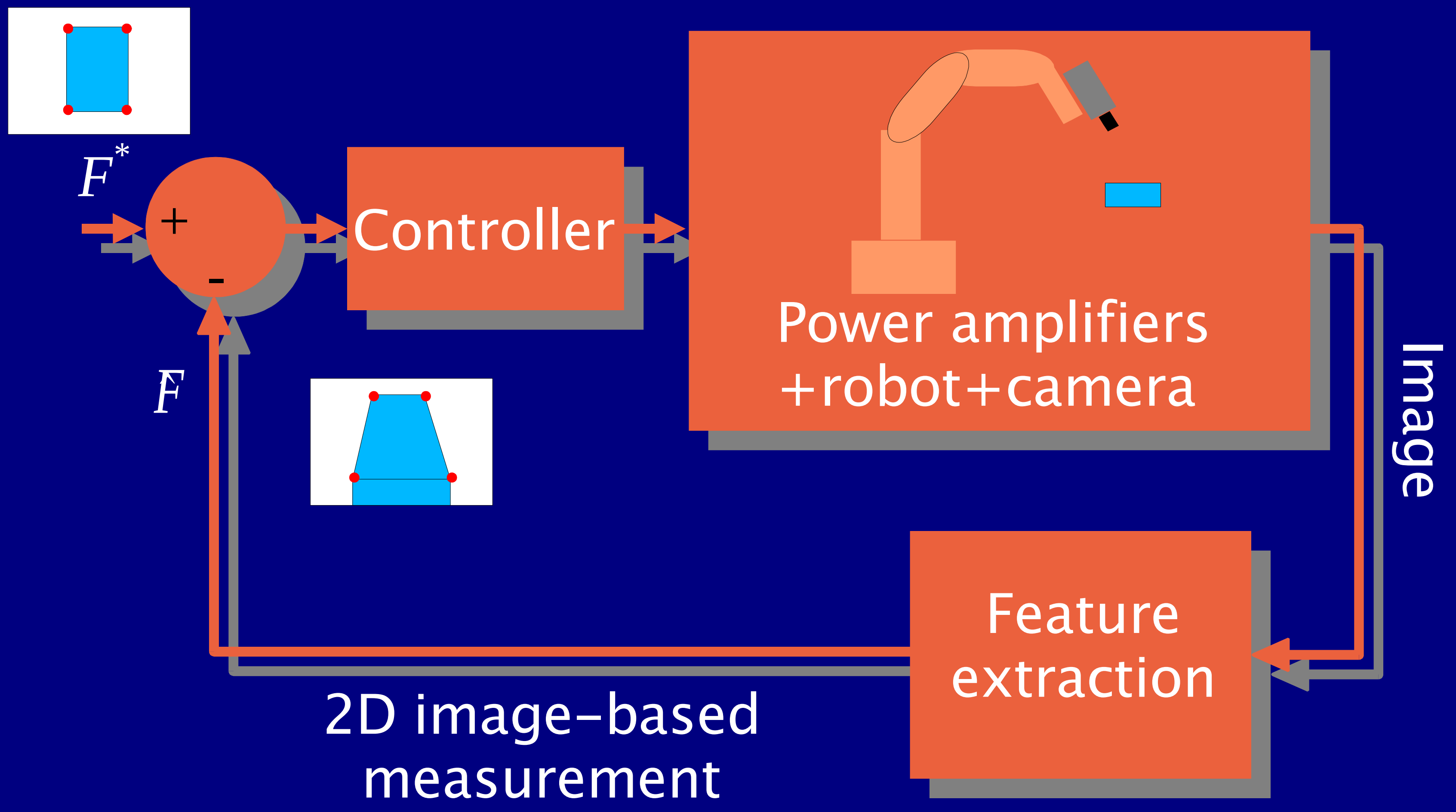


Eye to hand configuration

1. Visual servoing
3D *vs* 2D visual servoing



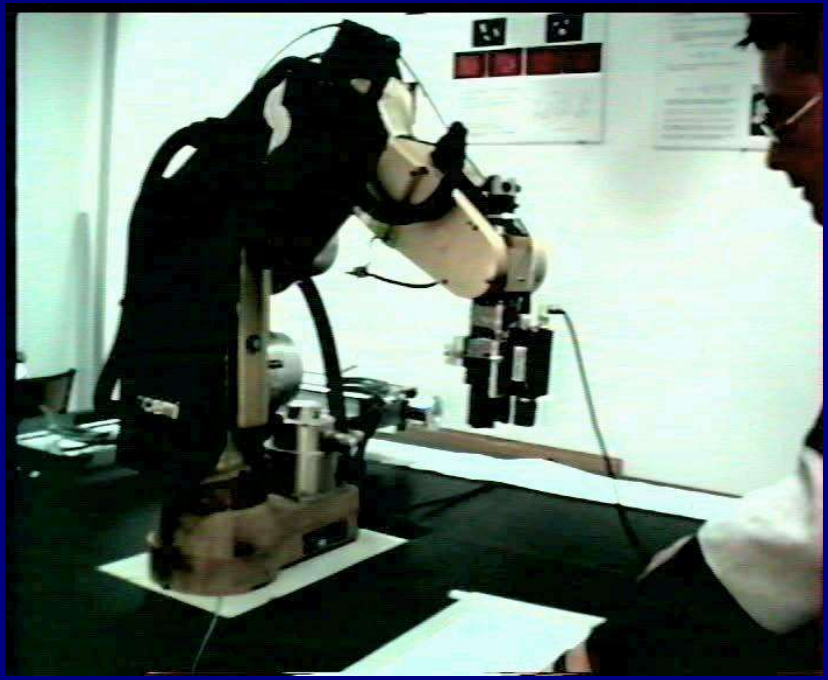
1. Visual servoing
3D *vs* 2D visual servoing



1. Visual servoing
Need for speed

- Need for high dynamic performances :
  - Fast target tracking (tracking of bacterias)
  - Fast sorting (picking up parts on a conveyor)
  - Motion compensation (heartbeat compensation)
- Requirements :
  - Fast camera (>50 Hz)
  - Fast robot
  - Real-time software environment
  - Accurate model of the dynamics

1. Visual servoing
Examples of high speed tracking



120 Hz
Gangloff ***et al.*** , 1999

1000 Hz
Nakabo ***et al.*** , 2000

1. Visual servoing
Dynamics of the image acquisition process

charge accumulation | transfer to board | transfer to memory | Image processing

T | T | <T | T | time

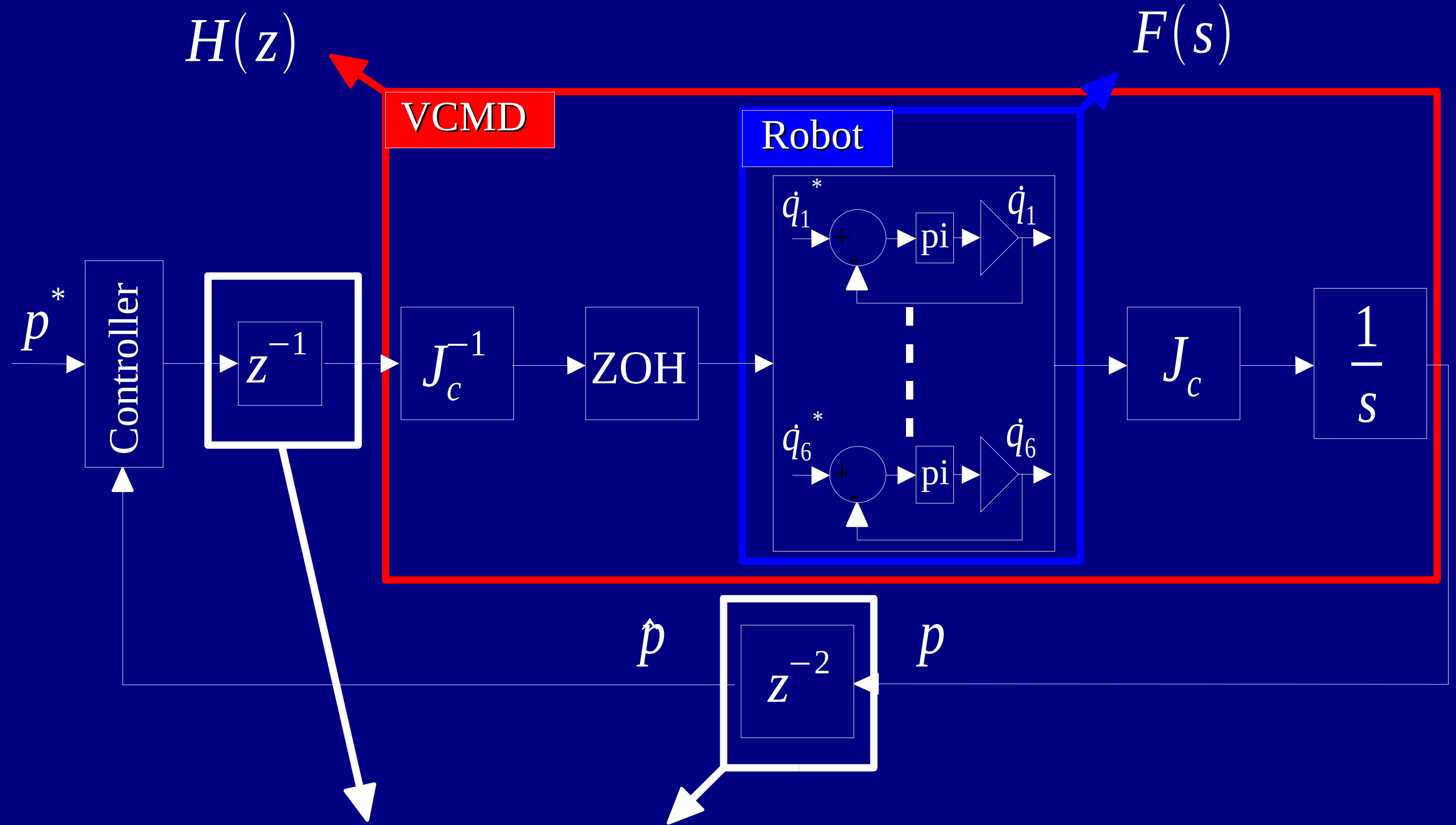
3T<Delay<4T

T=sampling period (***e.g.*** 2ms with a 500Hz camera)

1. Visual servoing
Dynamics of the manipulator

Model of the virtual robot

Model of the robot



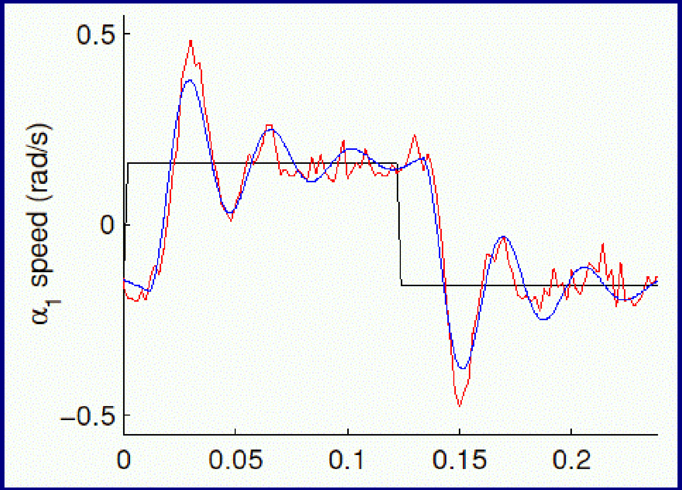
Model of the acquisition process

Gangloff, J. A. and de Mathelin, M. F., High speed visual servoing of a 6 manipulator using multivariable predictive control, ***Advanced robotics***, 2003 , 17 , 993-1021.

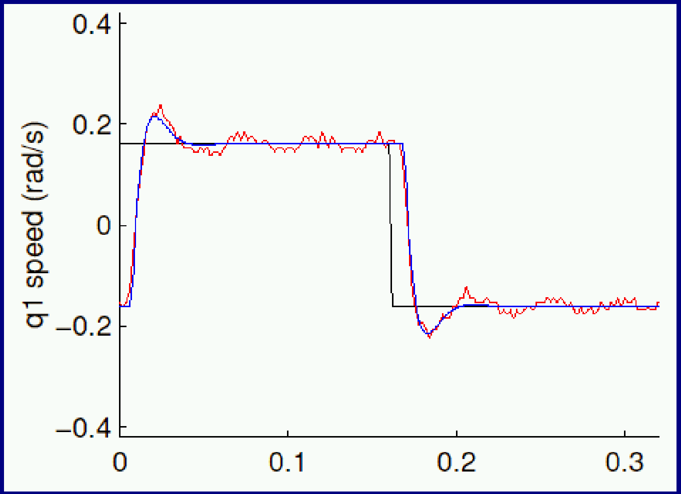
1. Visual servoing
Specific issues with medical robots

- Medical robots must be :
  - SAFE
  - COMPACT

⇒ Light structure ⇒ Flexibilities



Flexibilities identified



Flexibilities neglected

2. Applications in the medical field
Robotized laparoscopic surgery – endoscope control

- Taylor ***et al.***, 1995
  - Robotic assistant
  - Automatic centering of selected anatomic structures
  - Look then move visual servoing
  - 3D reconstruction by triangulation
- Casals ***et al.***, 1995
  - Tool tracking
  - Markers attached to the tools : features = lines
  - 3D visual servoing

2. Applications in the medical field
Robotized laparoscopic surgery – endoscope control

- Uecker ***et al.***, 1995
  - Tool tracking
  - Color markers
  - 2D visual servoing : centering and size
- Wei ***et al.***, 1997
  - Color markers : green is proven to be optimal
  - Stereo endoscope
  - 3D visual servoing

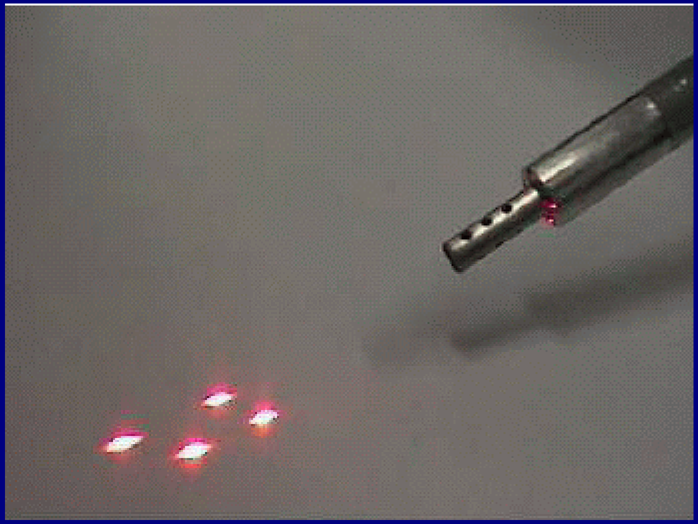
2. Applications in the medical field
Robotized laparoscopic surgery – tool control

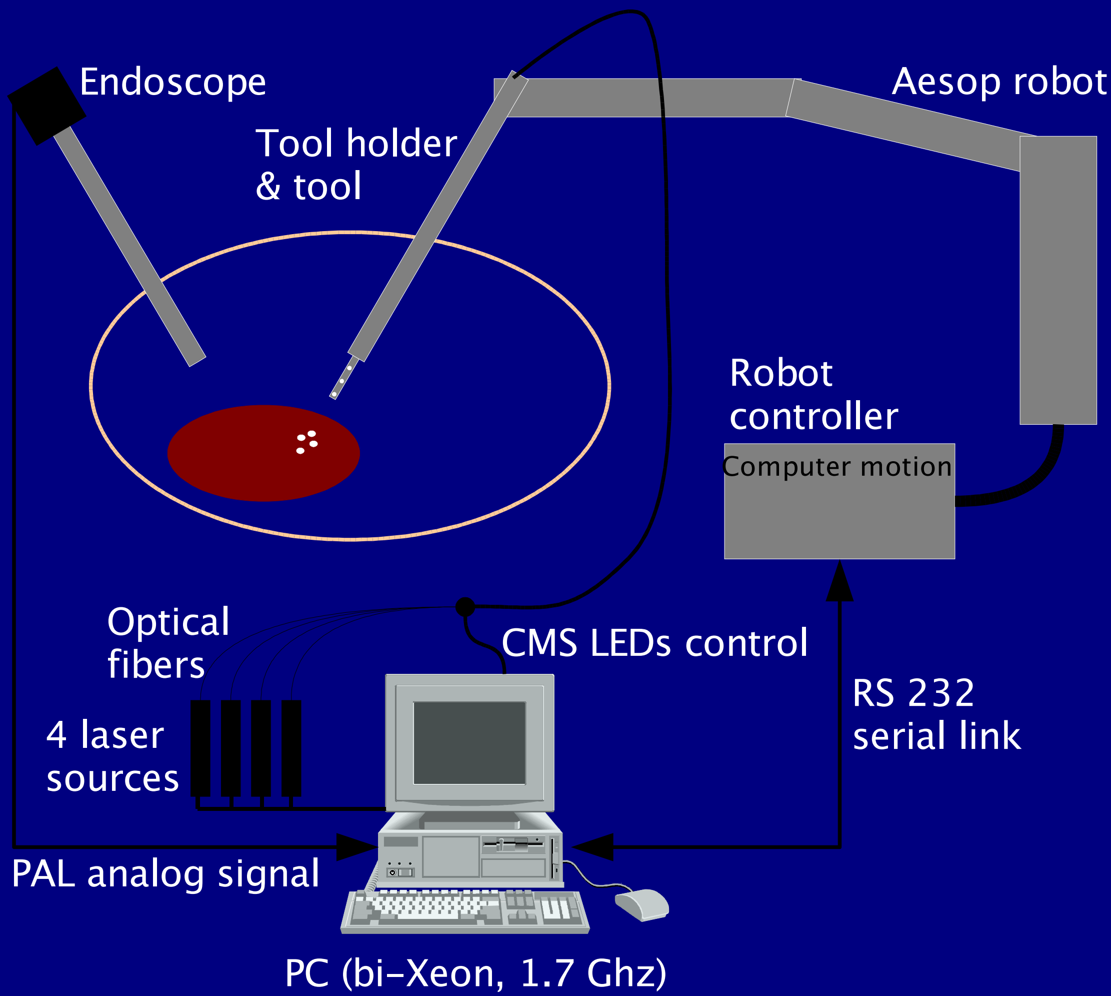
- Hayashibe and Nakamura, 2001
  - High-speed laser-scanner
  - 3D reconstruction of organ surface
  - Automatic positioning of instruments
  - External endoscope/instrument registration
- Krupa ***et al.***, 2003
  - Automatic retrieving of instruments
  - Laser pointer
  - Synchronized optical blinking features
  - Hybrid 2D1/2 visual servoing

2. Applications in the medical field

Example : automatic tool positioning

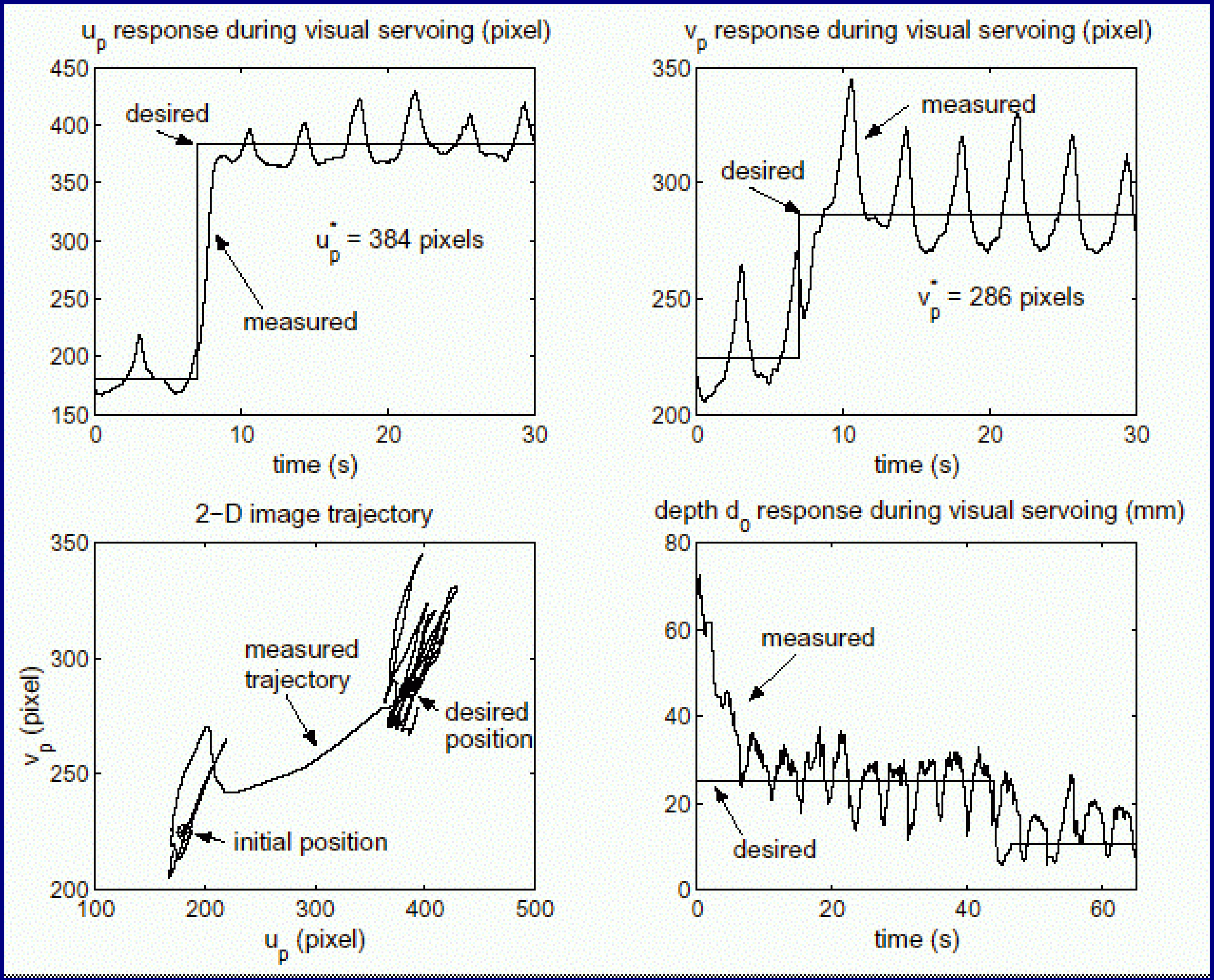
Laser-pointing tool-holder





2. Applications in the medical field

Example : automatic tool positioning



3. Physiological motions
Overview

- 2 main sources in the body :
  - Respiration
  - Cardiac beating
- Disturbance for the surgeon
- Current workarounds
  - Respiration : stopping the ventilator
  - Cardiac beating : stopping the heart, stabilizers
- Future solution : active robotic filtering

3. Physiological motions
Respiration

Clifford ***et al.***, Assessment of Hepatic Motion Secondary to Respiration for Computer Assisted Interventions ***Computer Aided Surgery***, 2002 , 7 , 291-299

Table 1. Hepatic Motion Secondary to Respiration in Nine Human Studies

Study/date	Number of subjects	Cranio-caudal (mm) Quiet inspiration	Cranio-caudal (mm) Deep inspiration	Anterior-posterior (mm)	Lateral (mm)	Modality
Weiss (1972)[32]						
(using scintigraphy)	12	11 ± 3	12–75			Scintigraphy
(using fluoroscopy)	25	13 ± 5				Fluoroscopy
Harauz (1979)[33]	51	14				Scintigraphy
Suramo (1984)[34]	50	25	55			US
Korin (1992)[35]	15	13	39	2.5		MRI
Davies (1994)[27]	9	10 ± 8	37 ± 8			US
Herline (1999)[13]	2	10.8 ± 2.5				Optical tracking
Shimizu (1999)[37]	1	21		8	9	MRI
Shimizu (2000)[36]	6	10.6 ± 7.0		4.6 ± 1.6	5.2 ± 1.8	MRI
Rohlfing (2001)[38]	4	12–26		1–12	1–3	MRI

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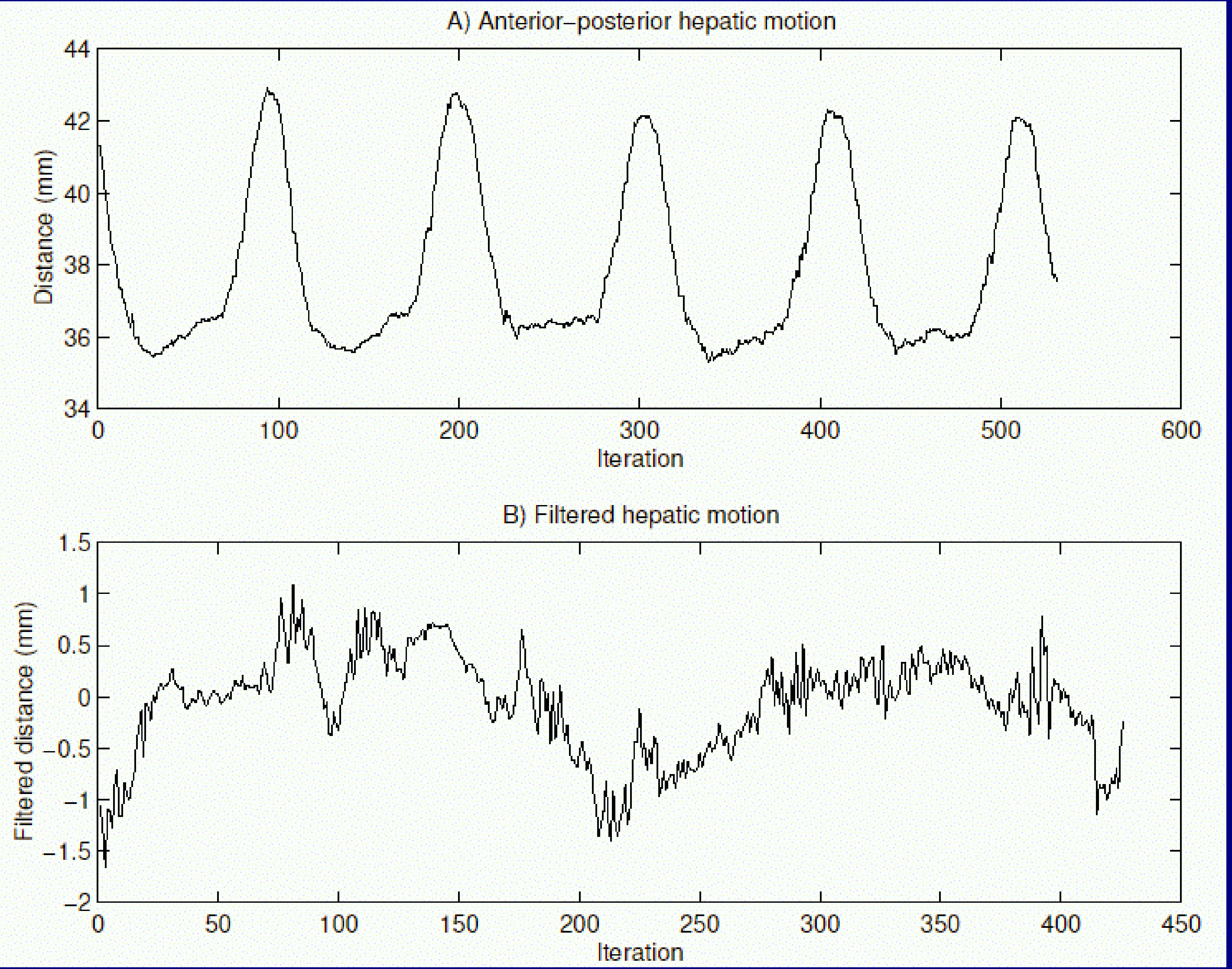
3. Physiological motions
Respiration – measurements* on a pig

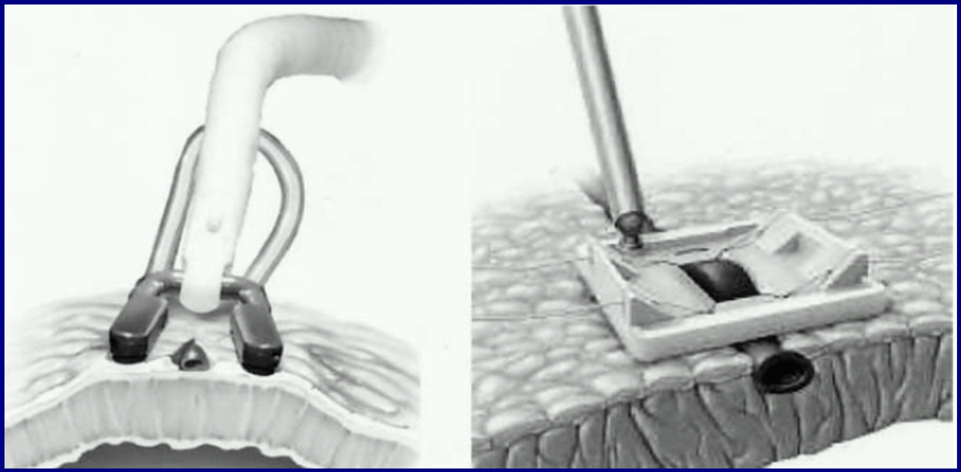
Hepatic motion measured on an anesthetized pig

Difference between two cycles

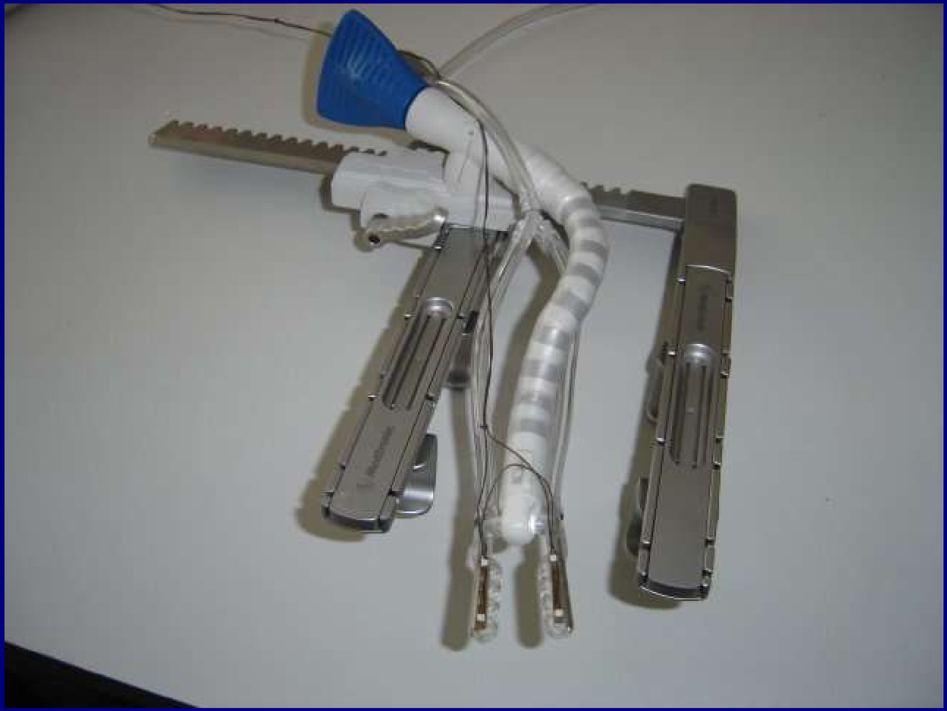


* Measurements acquired at 25 Hz with a CCIR camera

3. Physiological motions
Cardiac beating –stabilizers



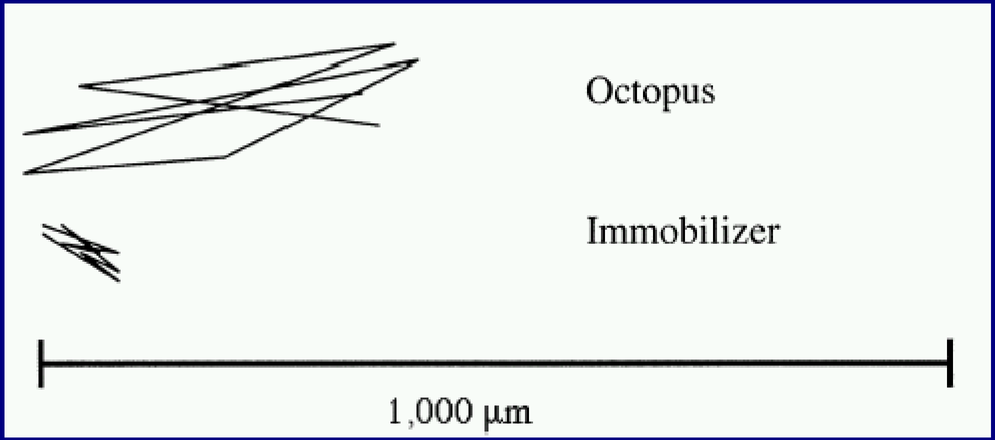
Octopus (medtronic) ***vs*** immobilizer (Genzyme)



Medtronic
Octopus 4.3

3. Physiological motions
Cardiac beating – measurements on human heart

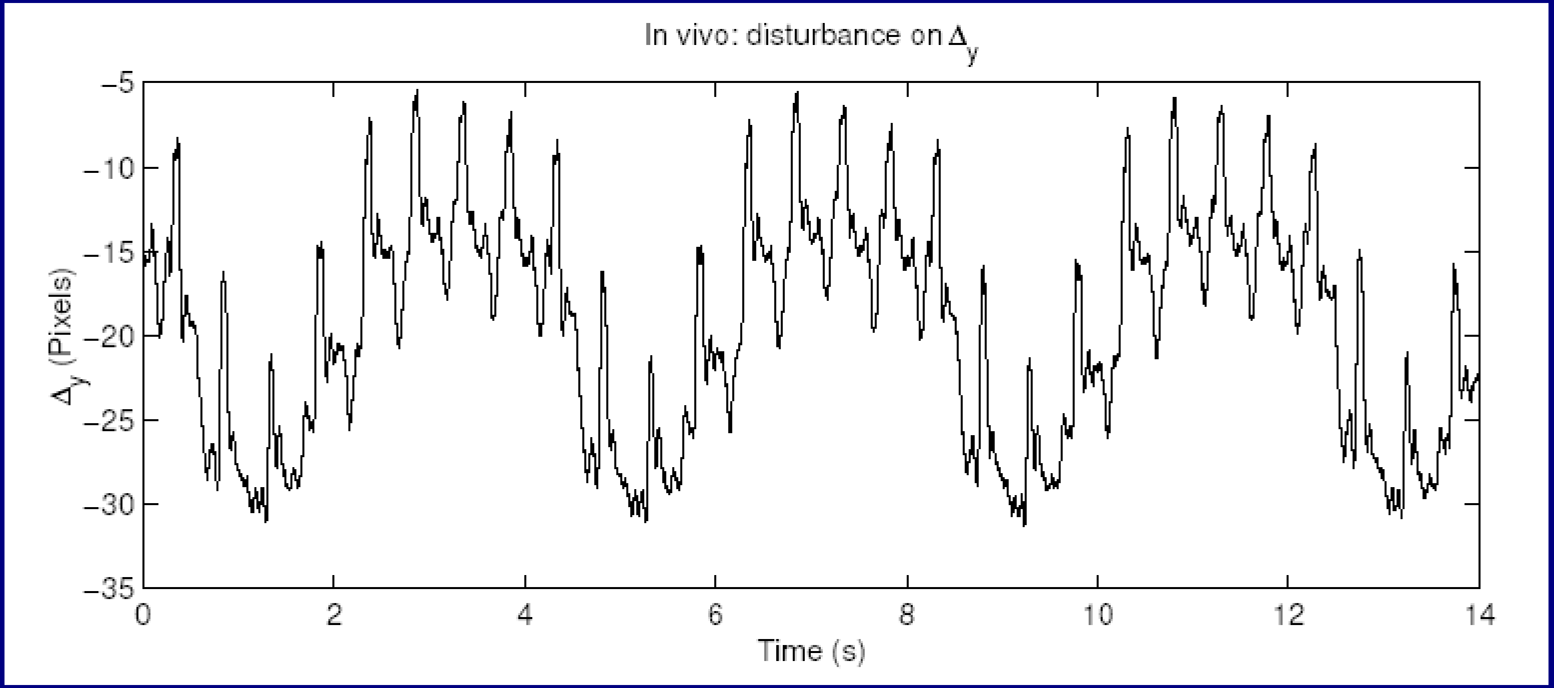
Detter ***et al.***, Comparison of two stabilizer concepts for off-pump coronary artery bypass grafting, ***Ann Thorac Surg***, 2002, 74:497-501.



Two-dimensionnal cardiac surface motion.
Technique using reflected polarized light.
Resolution : 1 μm
Octopus : 423 ± 129 μm
Immobilizer : 109 ± 32 μm

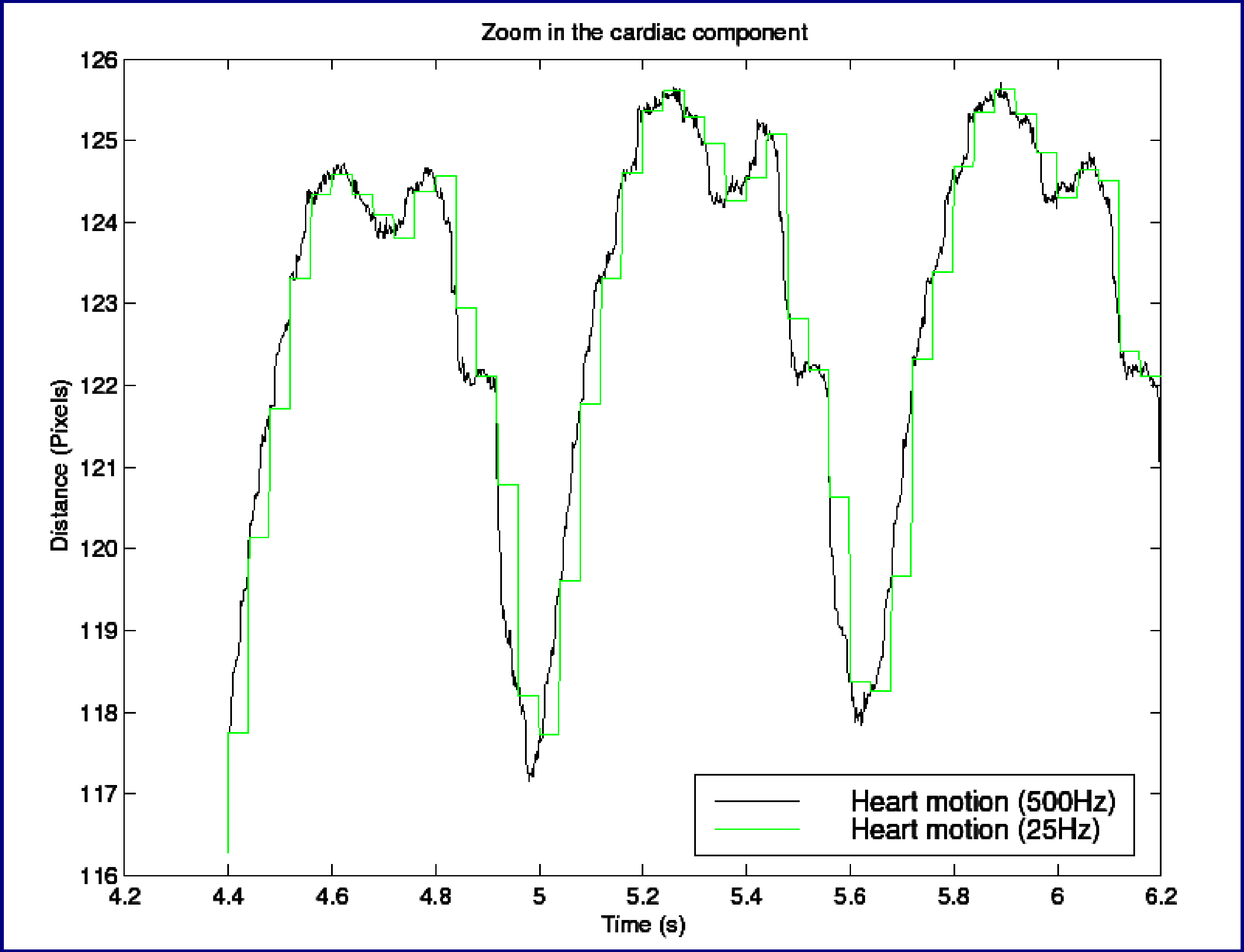
3. Physiological motions
Cardiac beating – measurements on a pig

Lateral motion of the heart of an anesthetized pig



Measurements acquired at 500 Hz with a high-speed camera. Ratio pixel/distance : 40 pixels/cm

3. Physiological motions
Cardiac beating – choice of the sampling frequency



3. Physiological motions
Conclusion

- Physiological motions are **repetitive**
- Respiration motion :
  - Slow
  - Forced by external ventilator ⇒ perfectly periodic
  - Large displacements of many organs
- Heart motion :
  - Fast
  - Combination of respiration motion and heartbeat motion
  - Small displacements restricted to the heart

4. Predictive/Repetitive control
Introduction

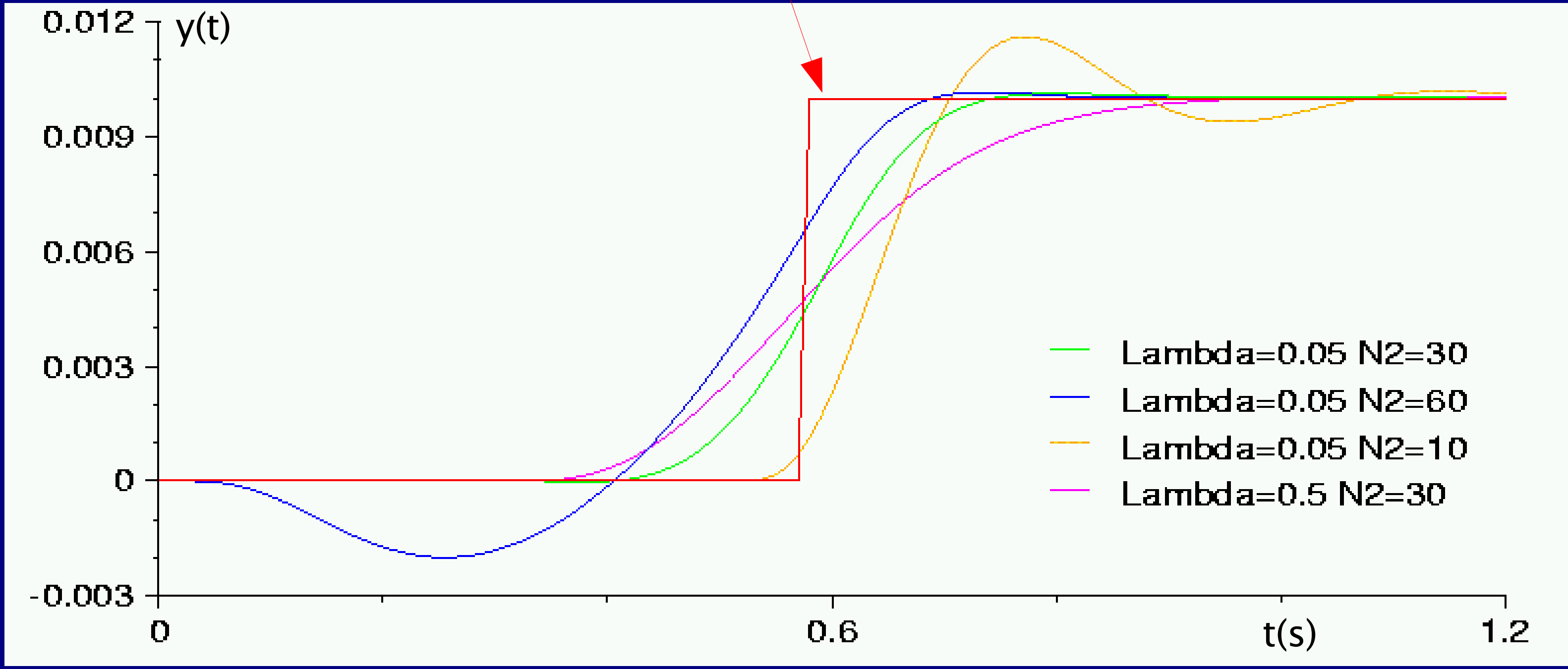
Minimization of :

control increment

$$\sum_{j=N_1}^{N_2}\left[y(t+jT)-r(t+jT)\right]^2+\lambda\sum_{j=1}^{N_u}\left[\Delta u(t+(j-1)T)\right]^2$$

measurement

reference



4. Predictive/Repetitive control
Repetitive control

Model of the dynamics in the ARIMAX form :

$$A(q^{-1})y(t) = q^{-1}B(q^{-1})u(t) + \frac{C(q^{-1})}{D(q^{-1})}\xi(t)$$

filtering of the noise

white noise

Repetitive control : $D(q^{-1}) = (1 - q^{-1})(1 - \alpha q^{-T})$

$0 < \alpha < 1$ T=period of the disturbance

Further reading :

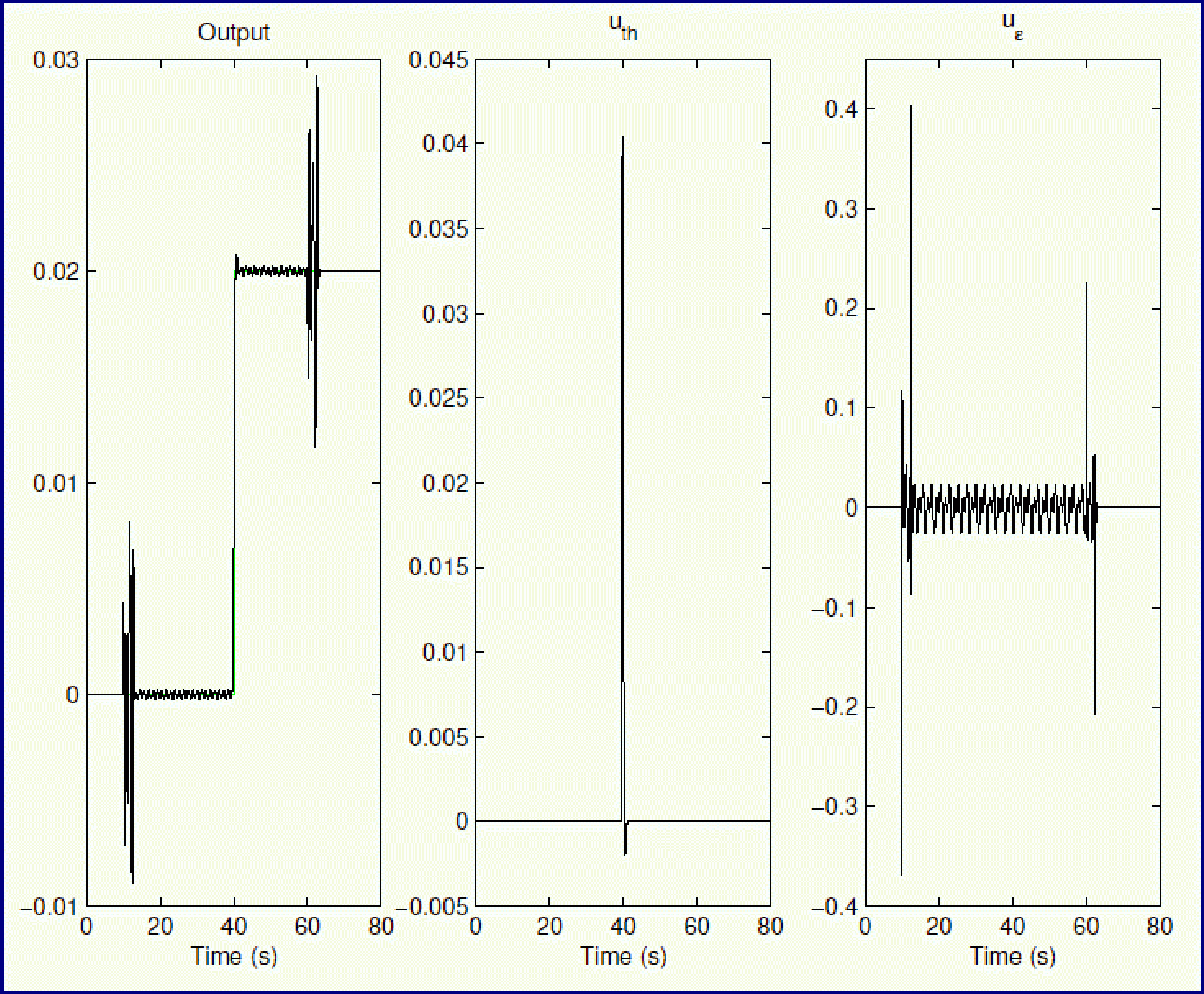
Camacho, E. F. and Bordons, C. Model predictive control
Springer Verlag, 1999

4. Predictive/Repetitive control
Repetitive control

Separation of the control in two components :

u_{th} reference tracking

u_{ϵ} disturbance rejection



4. Predictive/Repetitive control
Potential applications

- Predictive control :
  - Telemanipulation
  - Noise observer ⇒ anticipation of the disturbance
  - Automatic execution of predefined tasks
- Repetitive control :
  - Compensation of cyclic disturbances
  - Separation of disturbance rejection and reference tracking.

5. Active robotic filtering
Some existing works

- Riviere ***et al.***, 1998
  - Tremor cancellation
  - Active instrument
- Thakral ***et al.***, 2001
  - Rat heart wall motion analyze with fiber optic probe
  - Disturbance estimator : based on Fourier coefficients estimation
- Nakamura ***et al.***, 2001
  - Heartbeat synchronization
  - 1000 Hz heart tracking experiment

5. Active robotic filtering
Goal

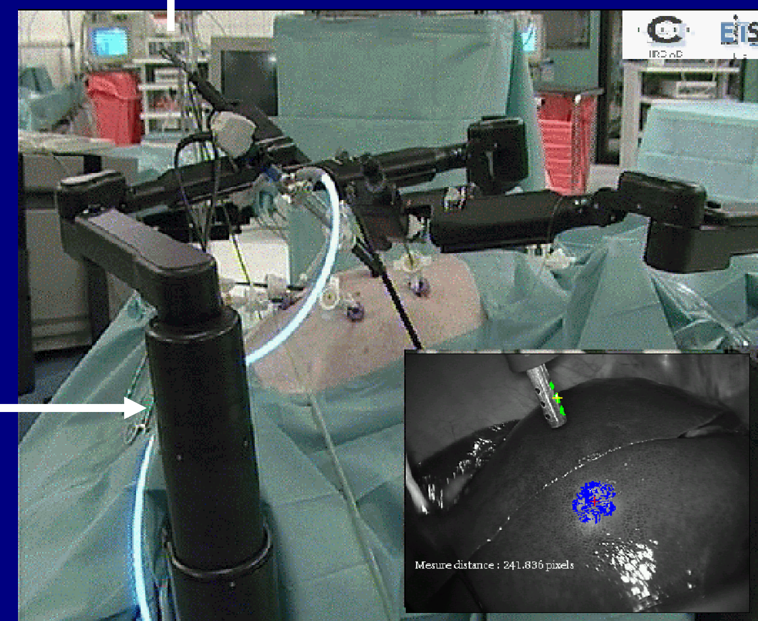
Filtered endoscopic view

Filter

Visual feedback

Controller

Master



Slaves

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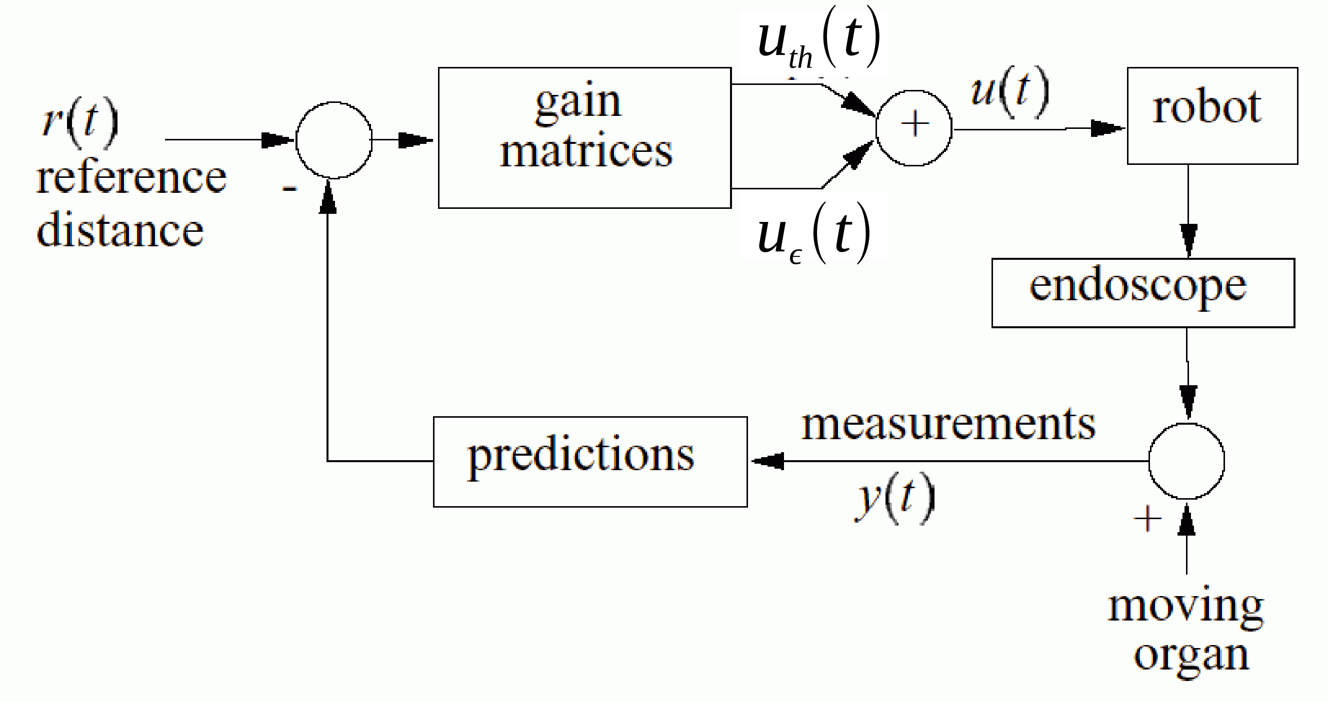
5. Active robotic filtering
Respiration – bloc diagram

- Anesthetized patient + artificial ventilation
  - Periodic motion
  - Repetitive control



5. Active robotic filtering
Respiration – testbed

500Hz camera

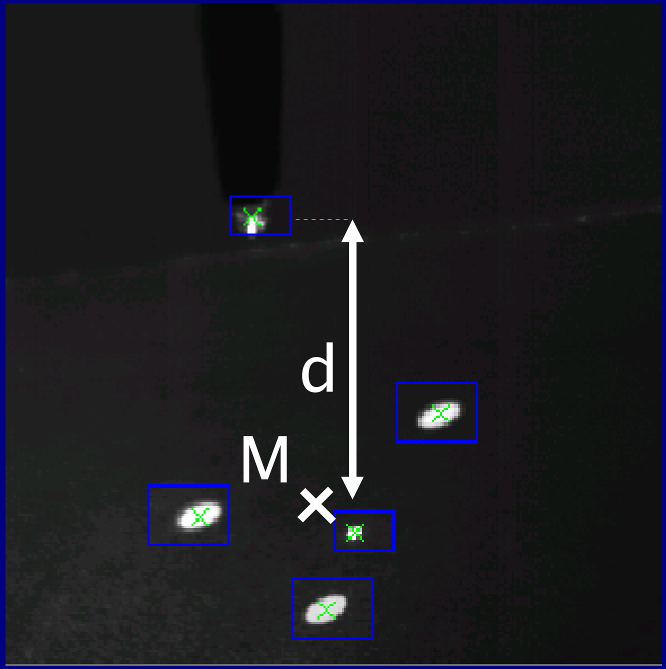
6 DOF robot

Laser source

LED

Organ simulator

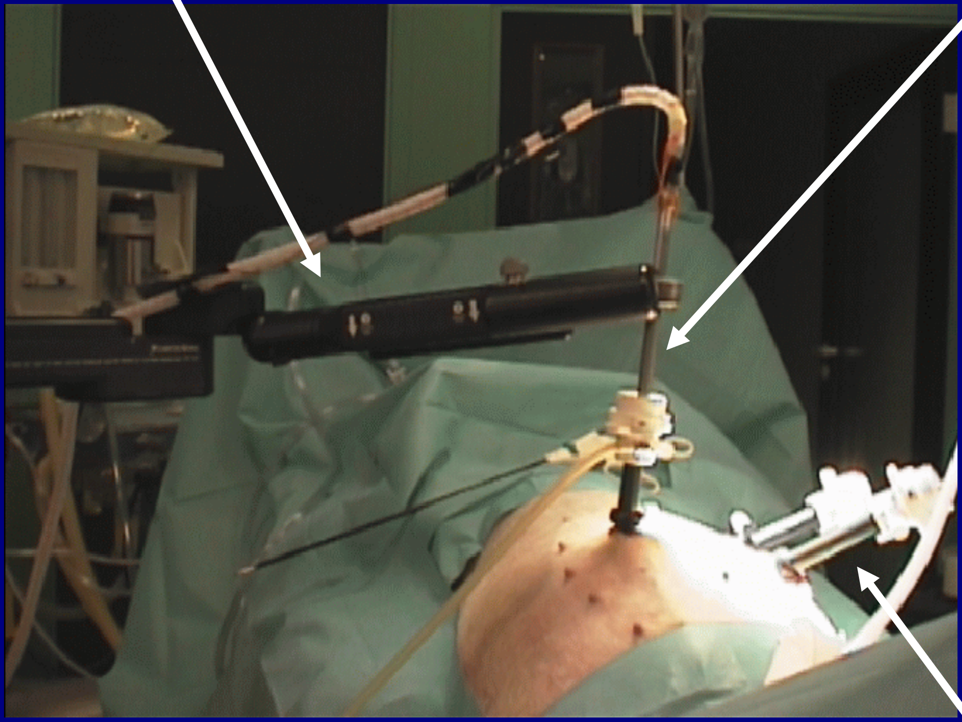
Visual feedback



5. Active robotic filtering
Respiration – *in vivo*

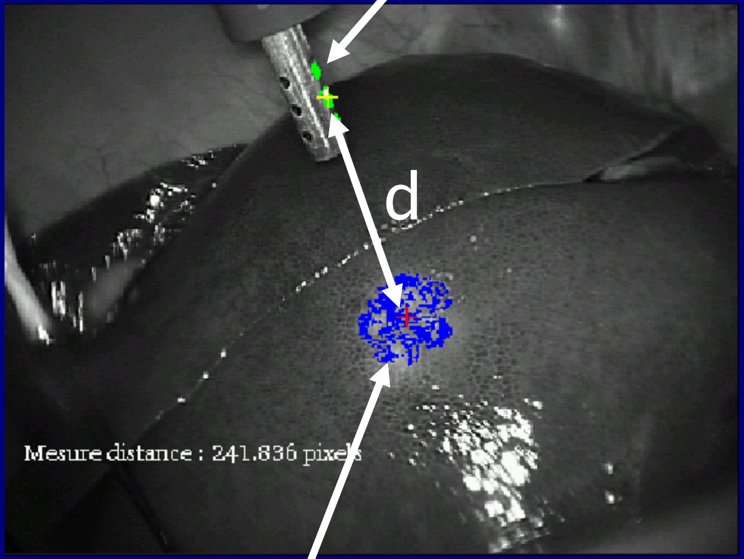
Aesop arm (computer motion)

Tool



LEDs

d



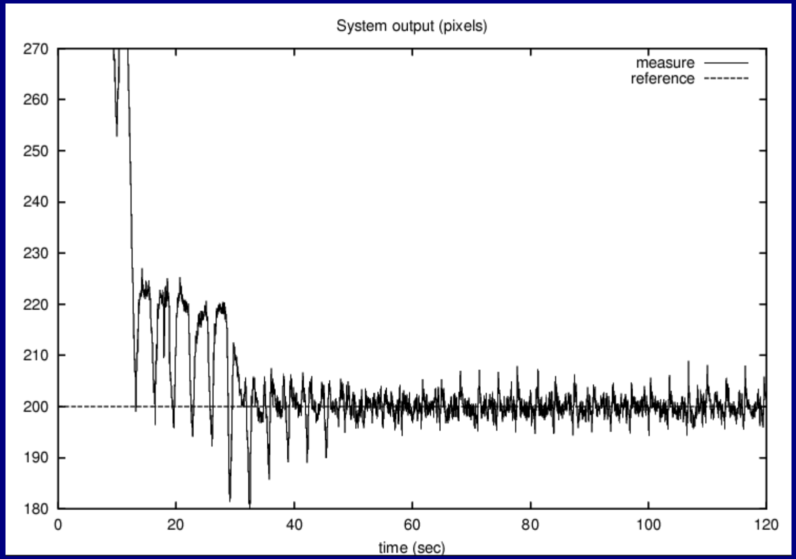
Laser spot

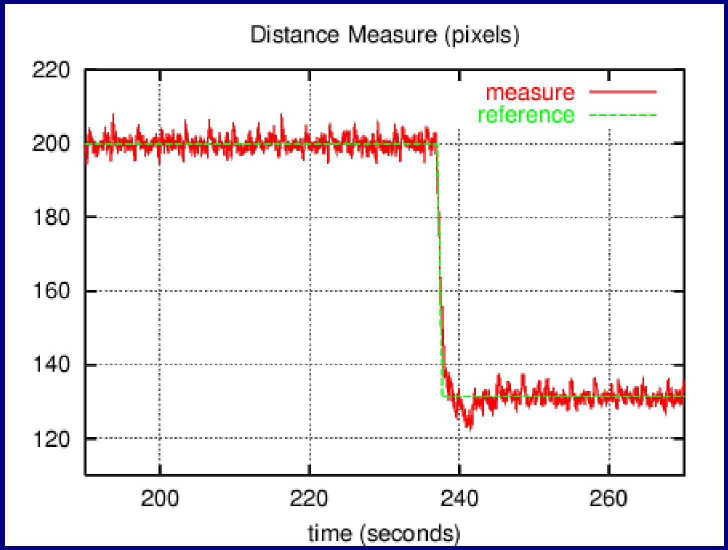
Endoscope trocar

5. Active robotic filtering

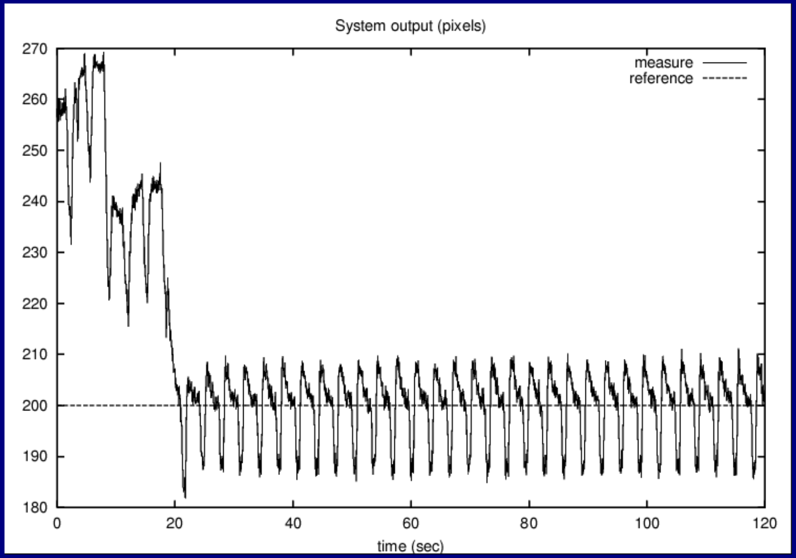
Respiration – results

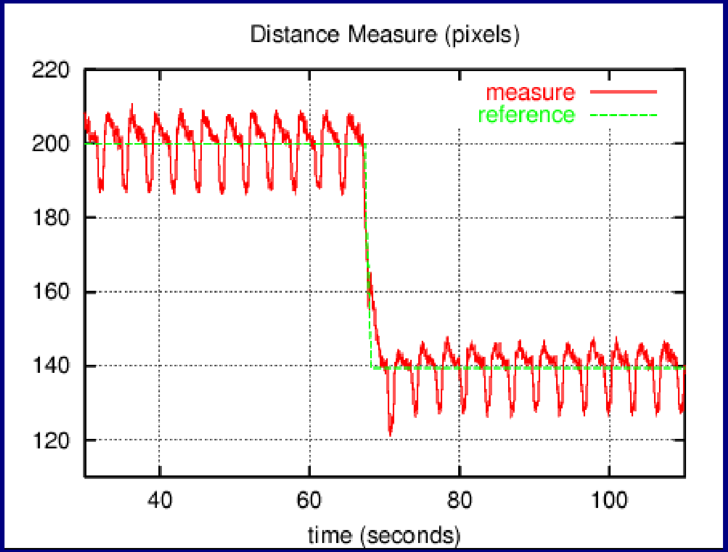
Repetitive control





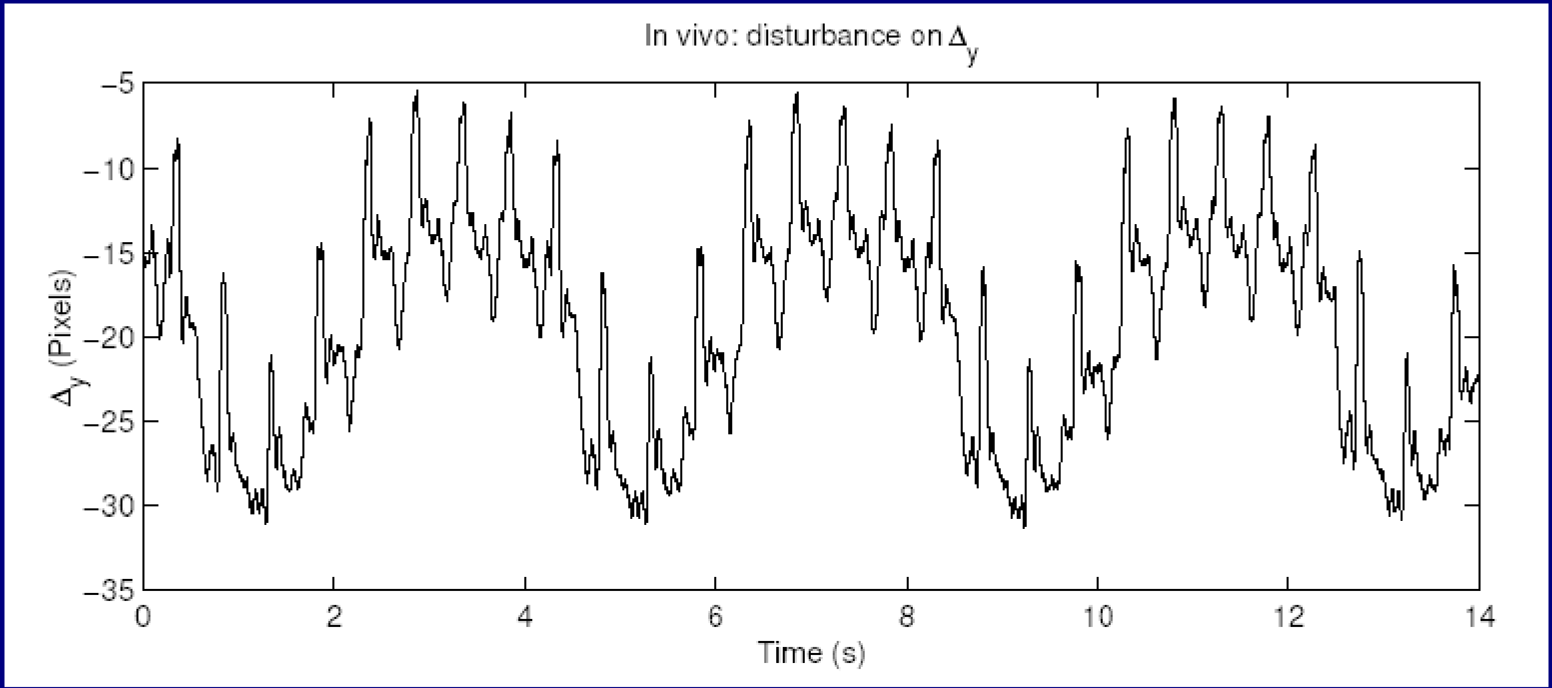
Standard control



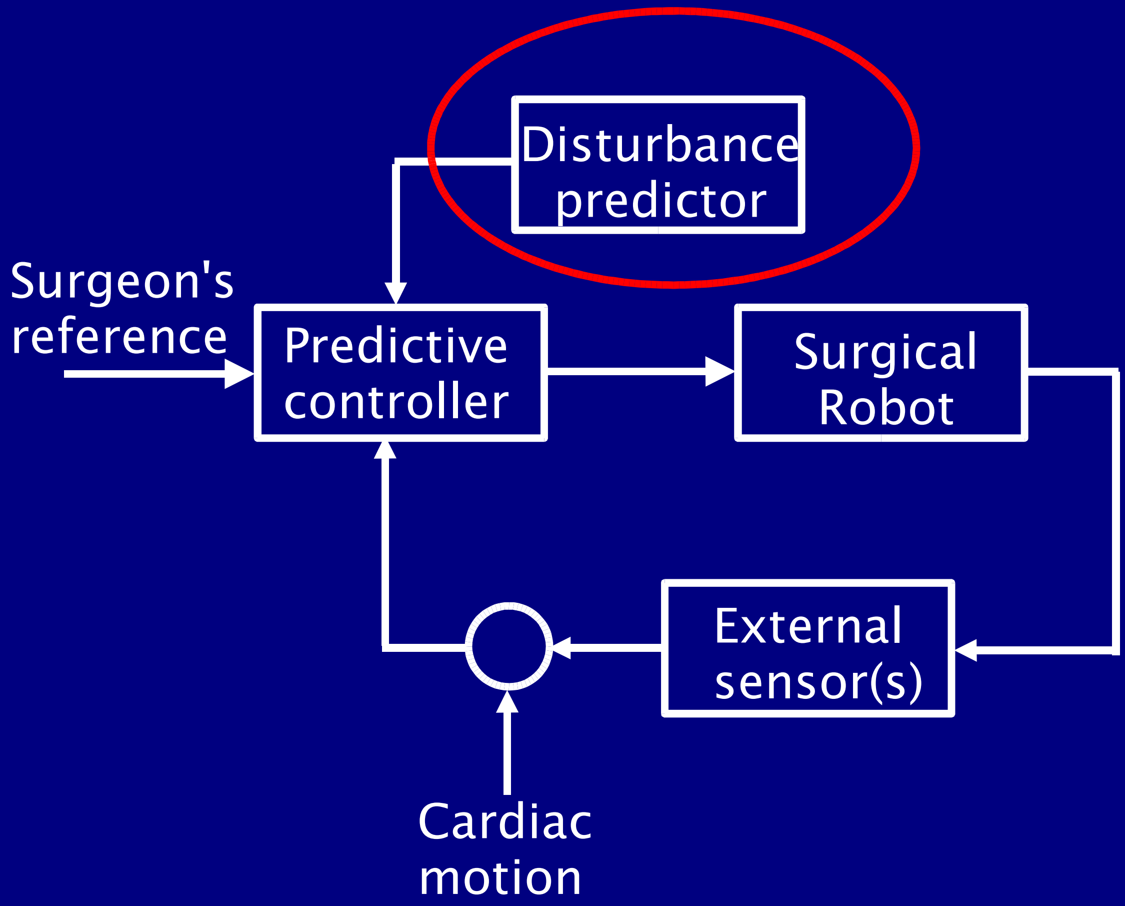


5. Active robotic filtering
Cardiac motion

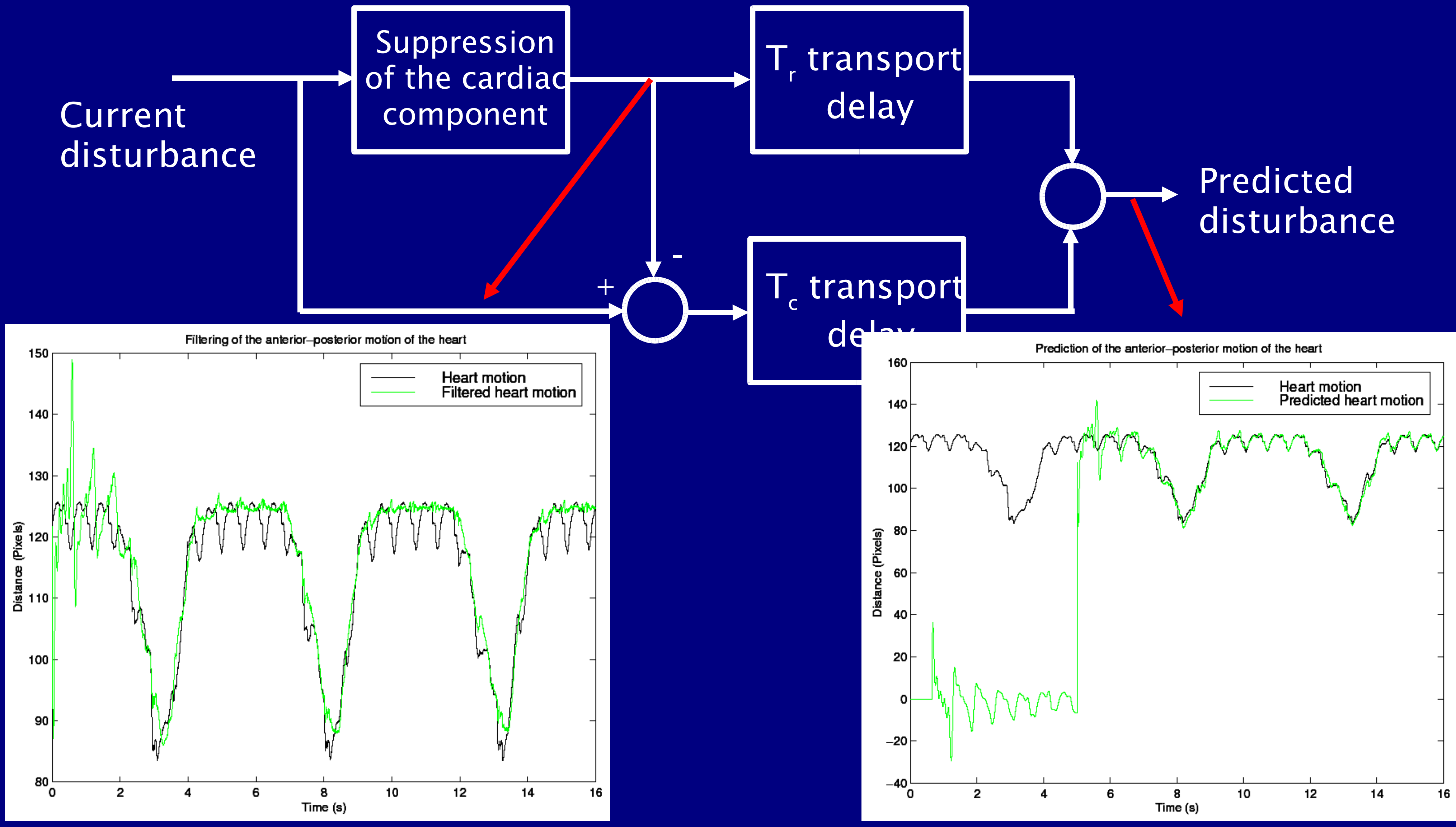
- Two non-harmonic periodic motions :
  - Respiration
  - Cardiac beating



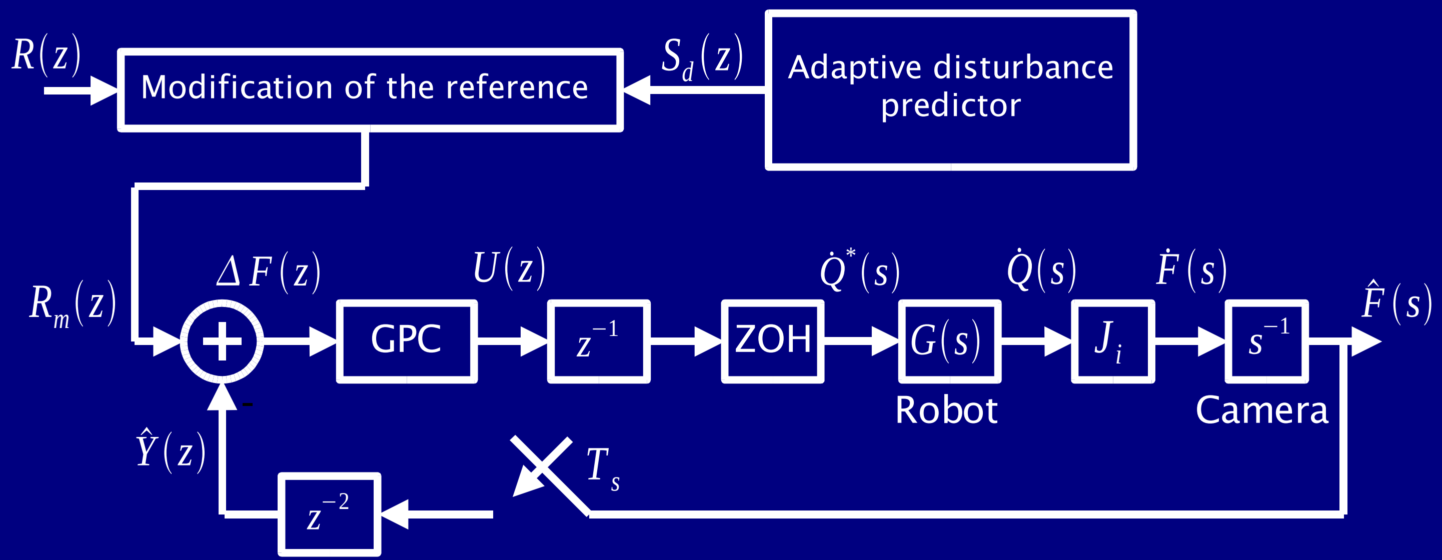
5. Active robotic filtering
Cardiac motion – predictive control strategy



5. Active robotic filtering
Cardiac motion – disturbance predictor

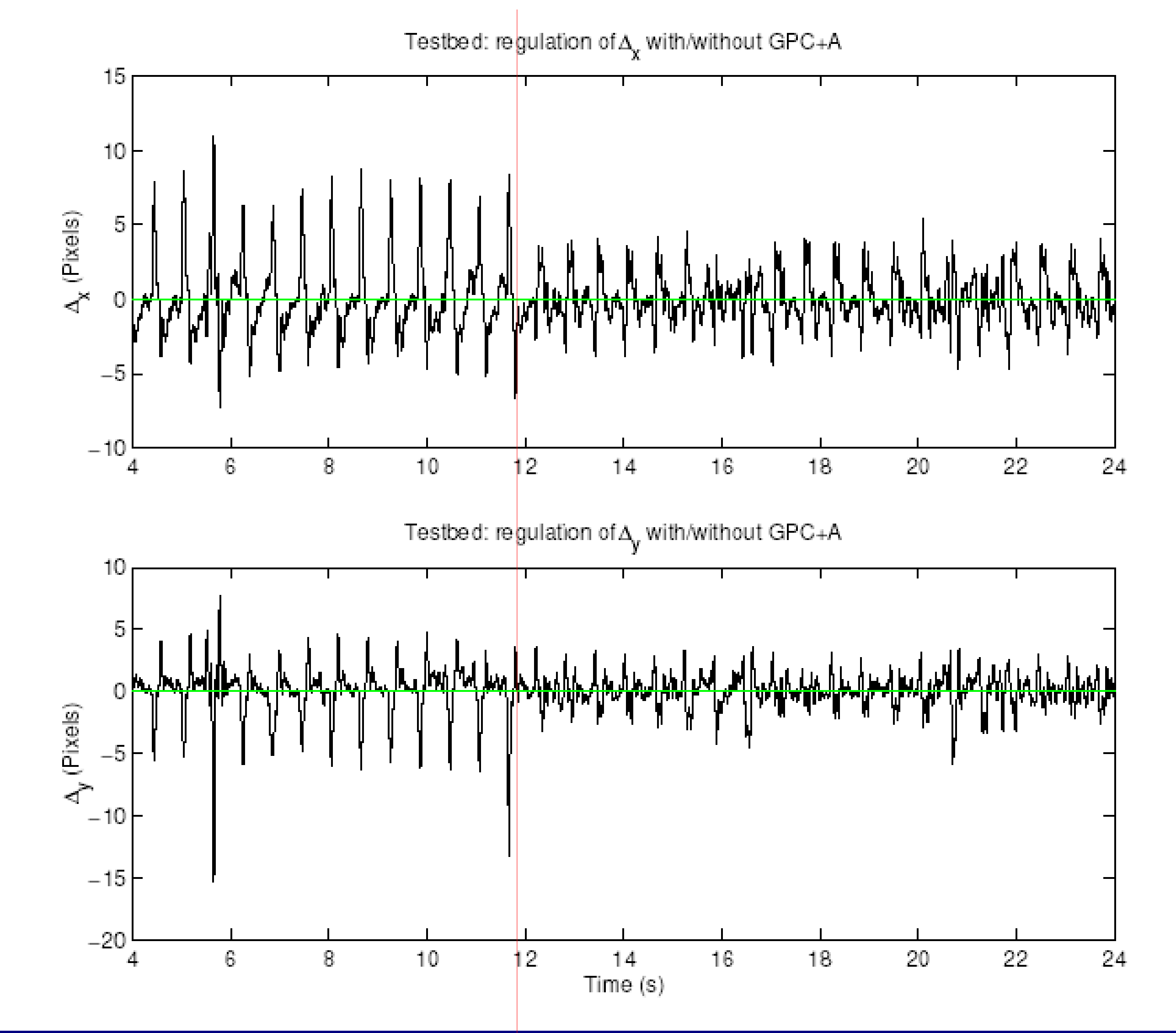


5. Active robotic filtering
Cardiac motion – bloc diagram



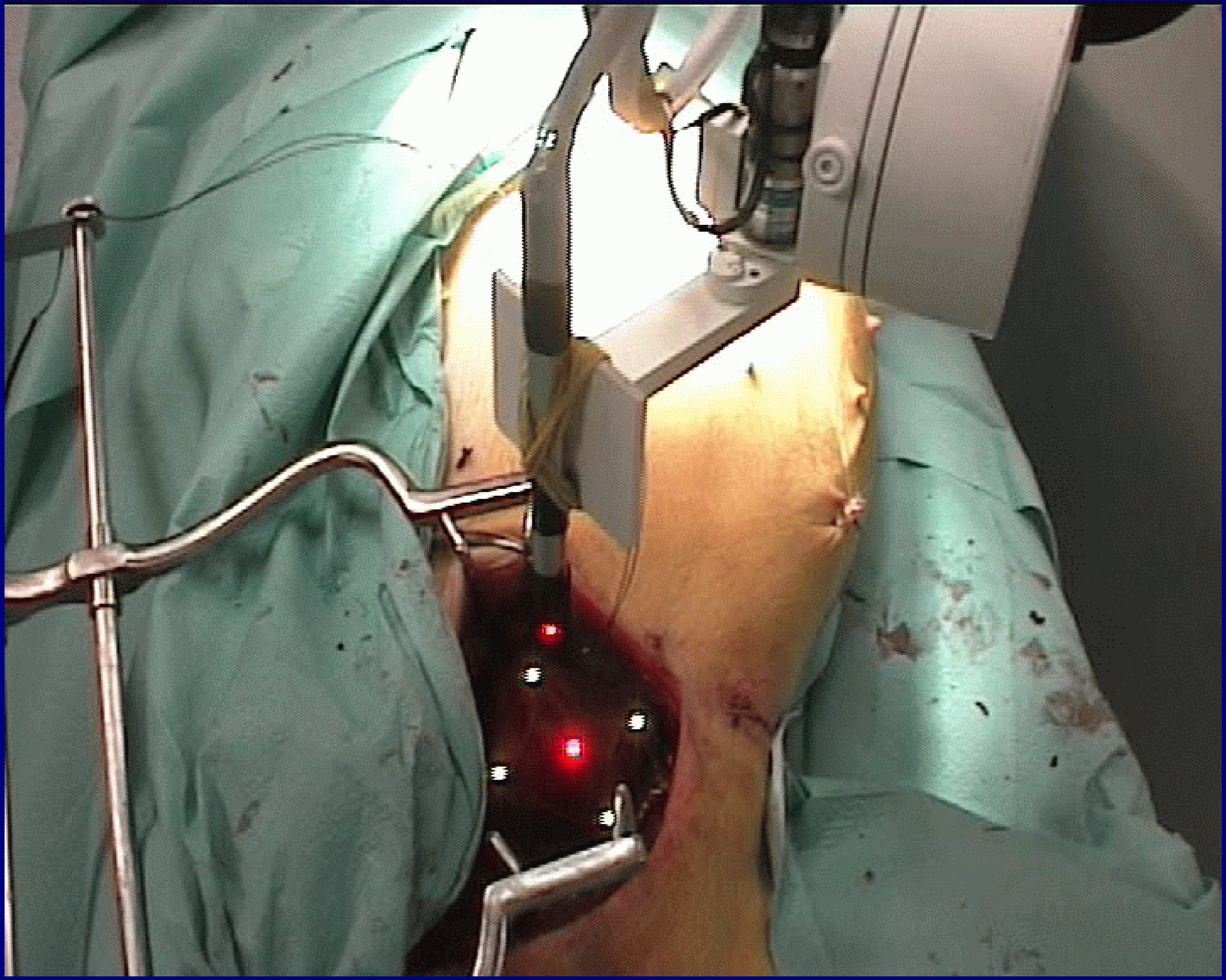
$$\frac{\hat{Y}(z)}{U(z)} = z^{-3}\mathbf{Z}\left(\frac{J_i G(s)}{s^2}\right)$$

5. Active robotic filtering
Cardiac motion – testbed results



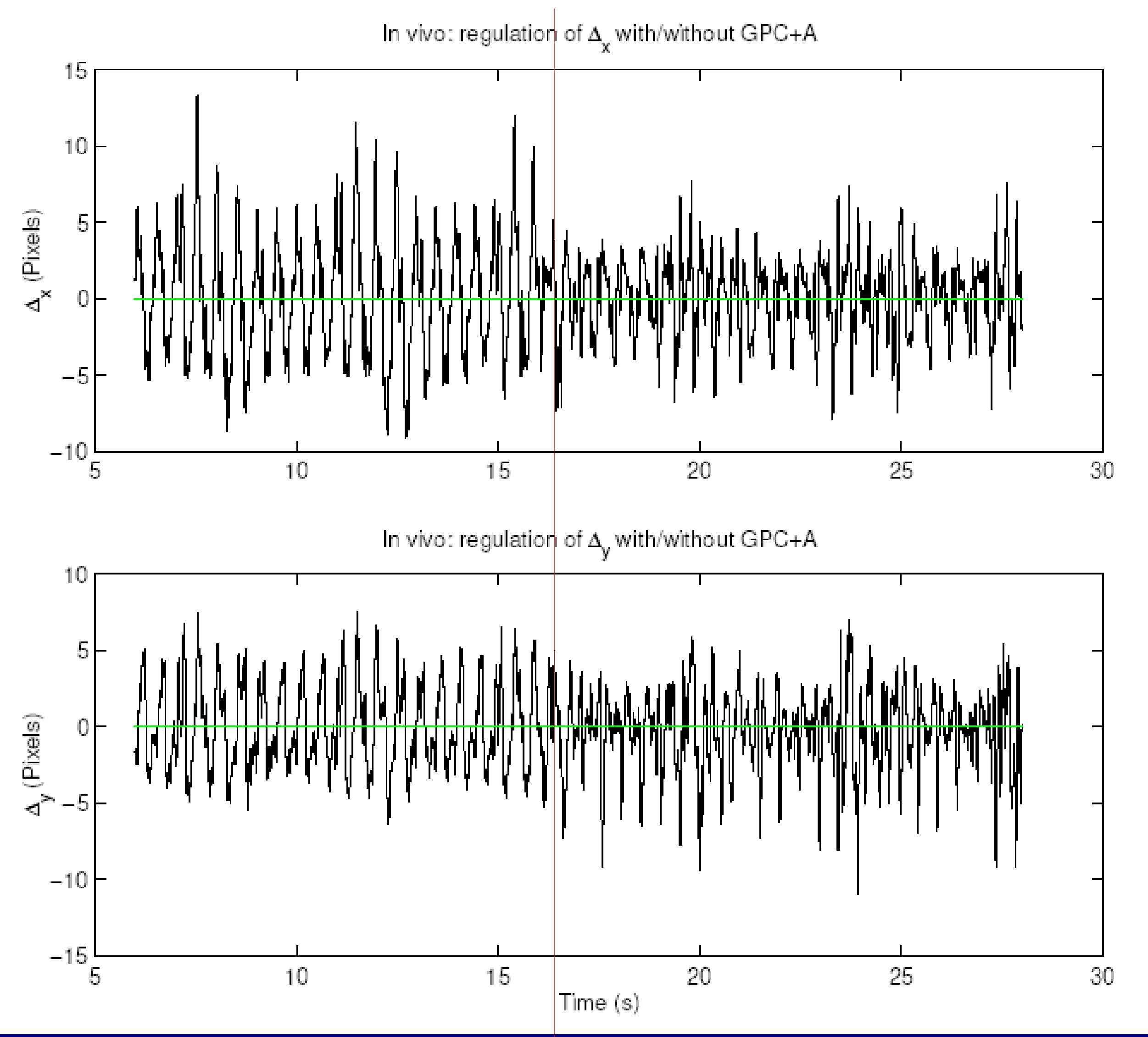
Disturbance estimator is switched on

5. Active robotic filtering
Cardiac motion – *in vivo* experiment



5. Active robotic filtering

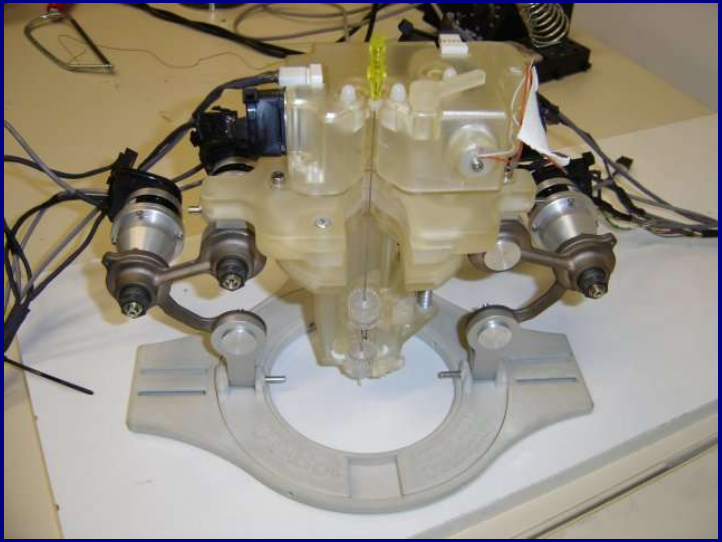
Cardiac motion – *in vivo* results



Disturbance estimator is switched on

6. Future

- Respiration compensation :
  - Use of pressure signals from the ventilator
  - Fusion of multiple measurement sources (***e.g.*** external camera + CT scan)
  - Fields of applications : laparoscopic surgery, interventional US, MRI or CT-scan, radiosurgery, ...



6. Future

- Cardiac motion compensation :
  - Use of ventilator pressure and ECG signals
  - Design of a dedicated structure
  - Adaptation to semi-endoscopic and totally-endoscopic constraints
  - Use of force feedback
  - Potential applications : MICABG, interventions inside the heart.