# Contributions to ultrasound visual servoing


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# Medical robotics

## Clinician assistance and medical gesture improvements

- **Teleoperated systems**
  - Duplicate clinician gestures

Da Vinci, Intuitive Surgical

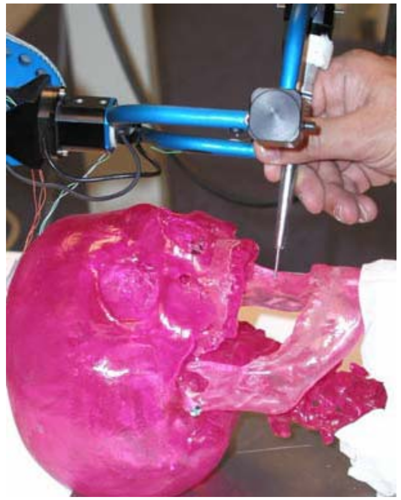
Estele, Robosoft

# Medical robotics

Clinician assistance and medical gesture improvements

- **Teleoperated systems**
  - Duplicate clinician gestures
- **Co-manipulated systems**
  - Constrain manual gestures of clinician in safe regions

Acrobot, Imperial College



Surgicobot, CEA LIST

# Medical robotics

Clinician assistance and medical gesture improvements

- **Teleoperated systems**
  - Duplicate clinician gestures
- **Co-manipulated systems**
  - Constrain manual gestures of clinician
- **Semi-autonomous or autonomous systems**
  - Automatically perform a part of intervention

MBARS

SCALPP, LIRMM

# Medical robotics

Clinician assistance and medical gestures improvements

- **Teleoperated systems**
  - Duplicate clinician gestures
- **Co-manipulated systems**
  - Constrain manual gestures of clinician
- **Semi-autonomous or autonomous systems**
  - Automatically perform a part of intervention
  - **Guidance from anatomical images**

MBARS

SCALPP, LIRMM

# Image-guided medical robots

- Guidance from pre-operative images
  - Robot trajectory pre-computed from pre-operative planning
  - Robot registration from both patient & image data
  - Open loop control

**Orthopedic surgery**

Robodoc

**Neurosurgery**

Neuromate

**Radiotherapy**

Cyberknife

Pro - Imaging modalities can be used

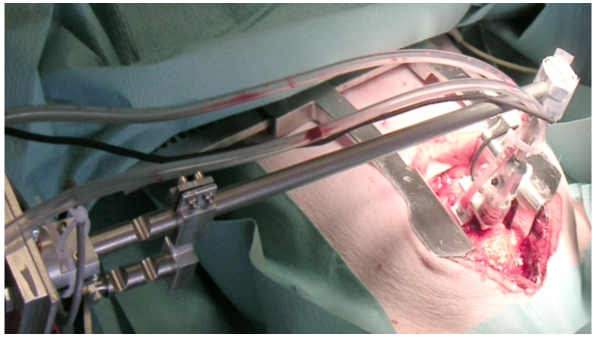
Cons - Calibration and registration error sensitivity

- Planning is valid only if anatomical target remains perfectly motionless

# Image-guided medical robots

- Guidance from per-operative images
  - Target directly defined in per-operative images
  - Robot trajectory online updated
  - Closed loop control

**Cardiac surgery**

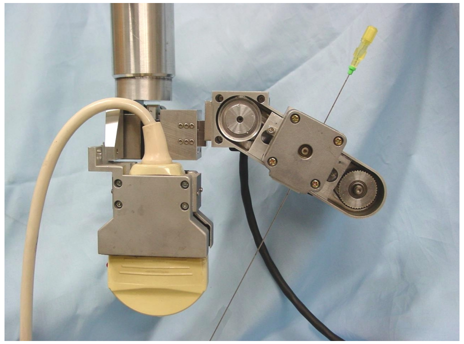


[Bachta08]

**Natural orifice surgery**


[Ott09]

**Interventional radiology**



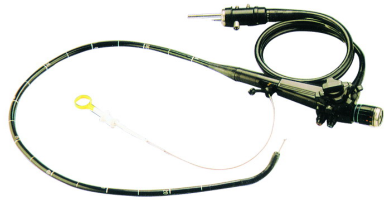
[Hong04]

Pro - Improved task accuracy
- Target motion compensation

Cons - Real-time & robust image processing needed

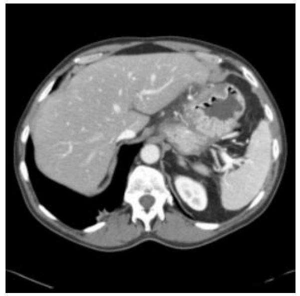
# Different medical modalities

– Optical images

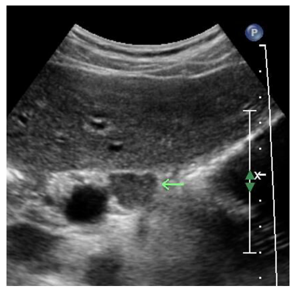


– MRI

– CT scan



– Ultrasound



# Per-operative medical imaging

| | Optical images | MRI | CT scan | Ultrasound |
|---|---|---|---|---|
| No invasive | o | ✓ | ✓ | ✓ |
| No ionizing | ✓ | ✓ | o | ✓ |
| Real time | ✓ | o | o | ✓ |
| Image quality | + | ++ | ++ | -- |

- Research area: US anatomical imaging guidance

# Research activity objectives

- **US visual servoing**
  - Providing generic solutions

- Focus on
  - Interaction modeling between the probe and the environment
  - Generic methods to control the 6 degrees of freedom (dof) of robotized probes
  - Real-time & robust visual information extraction

- Suitable for all applications requiring
  - Accurate positioning on anatomical sections
  - Physiological motion compensation

# Outline

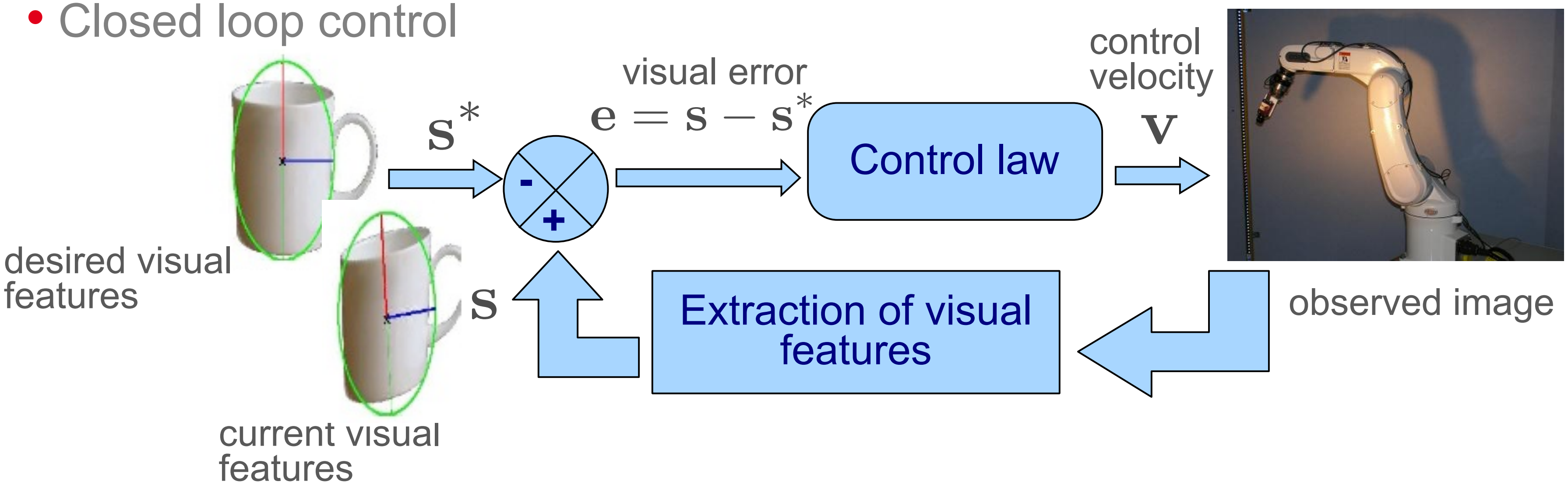
- US based visual servoing issues and contribution overview
- Part I: Approaches based on geometrical information
- Part II: Approaches based on dense information
- Conclusion and future works

# Outline

- **US based visual servoing issues and contribution overview**
  - Visual servoing principle
  - State of the art related to US visual servoing
  - Contribution overview
- **Part I: Approaches based on geometrical visual information**
- **Part II: Approaches based on dense visual information**

# Visual servoing: Principle

- Closed loop control

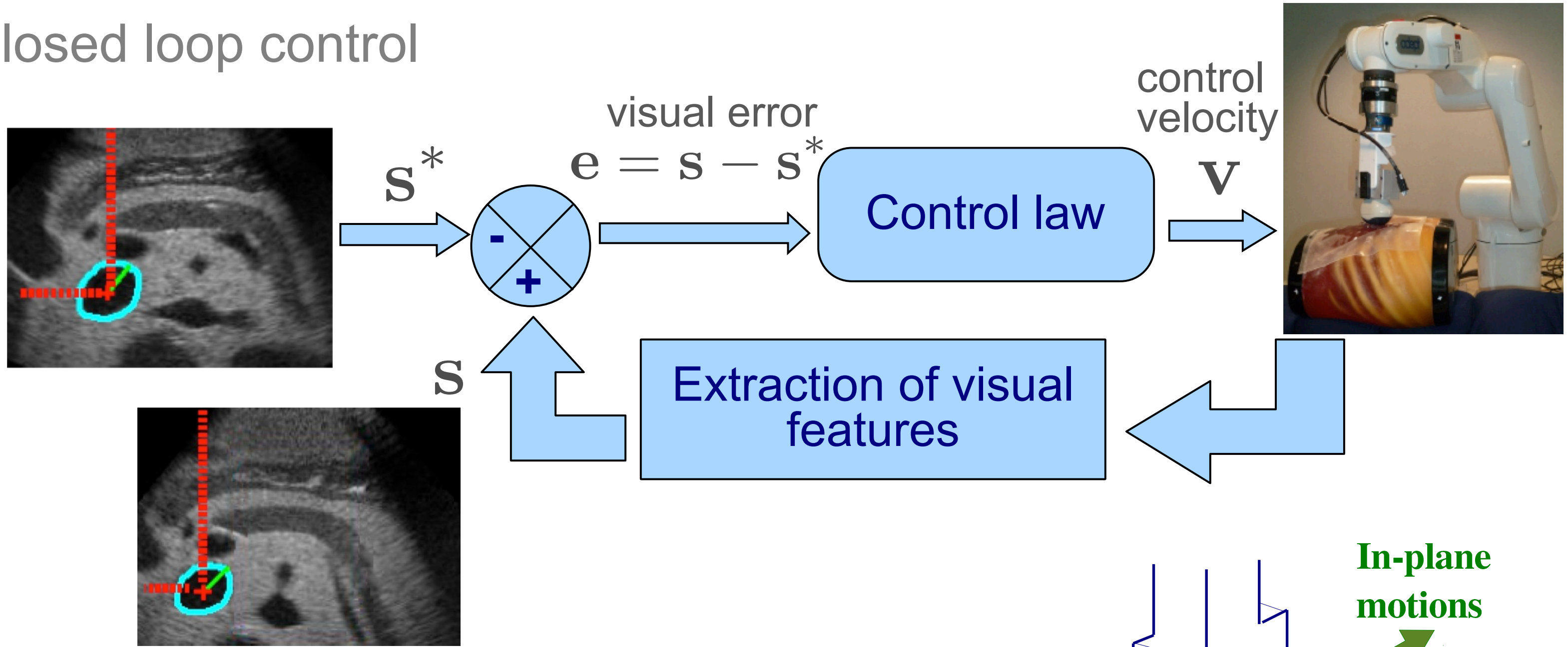



- Interaction modeling: $\dot{\mathbf{s}} = \mathbf{L_s}\mathbf{v}$

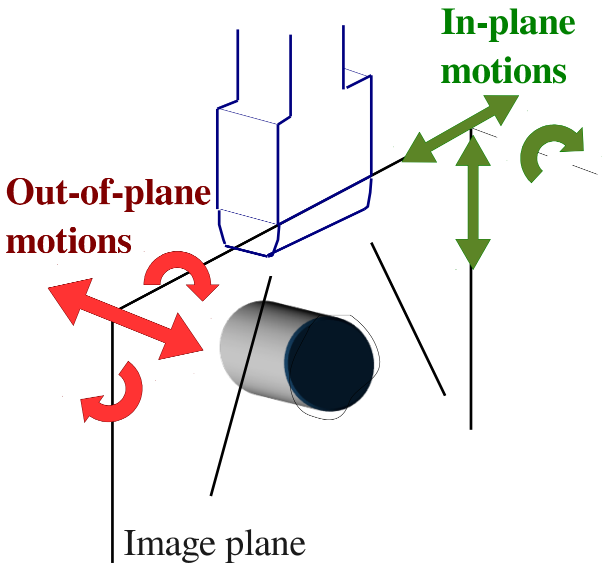
- Classical control law: $\mathbf{v} = -\lambda \widehat{\mathbf{L_s}}^{+} (\mathbf{s}(\mathbf{r}) - \mathbf{s}^*)$
  - Exponential decreasing of visual error

# Visual servoing: Camera versus US probe

- Closed loop control



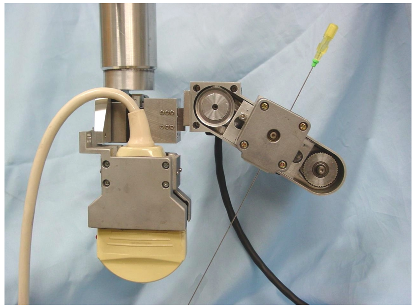

- Extension to ultrasound modality
  - No perspective projection
  - Full information in the image plane
- Challenges
  - Interaction modeling $\dot{\mathbf{s}} = \mathbf{L_s}\mathbf{v}$
  - Out-of-plane motion control
  - Low image quality

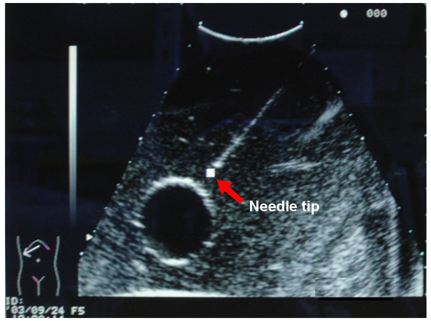


# State of the art: Eye-to-hand

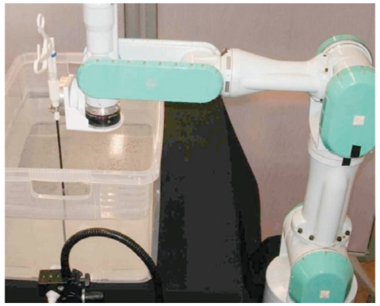
## New research topic since 2002

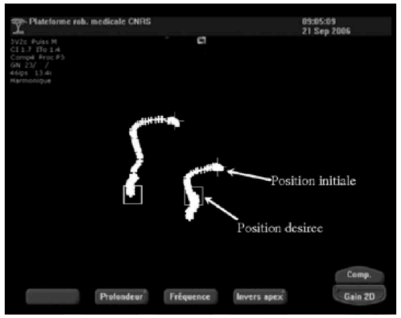
- Needle positioning
  - [Hong04 - Univ. of Tokyo], [Neubach10 - Israel Inst. of Tech.]
    - IBVS, 2 or 3 dof in plane





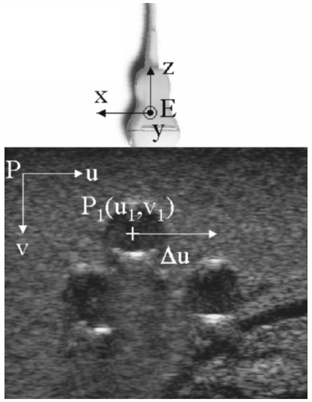

- Laparoscopic instrument positioning
  - [Novotny07 - Harvard]
    - PBVS, 4 dof
  - [Vitrani05, Vitrani07 - ISIR], [Sauvée08 - LIRMM]
    - IBVS based on tool model, 4 dof



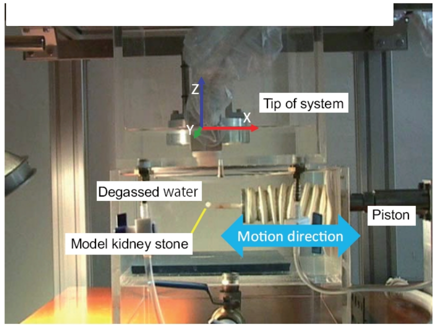


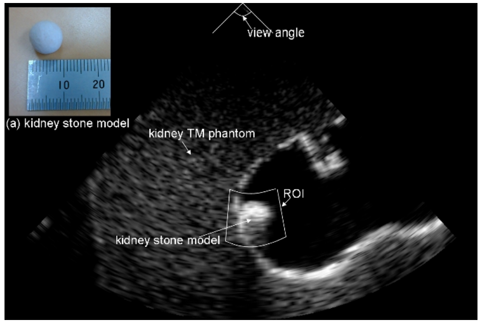
# State of the art: Eye-in-hand

- Positioning on carotid artery
  - [Abolmaesumi02 - British Columbia]
    - IBVS, 3 dof in plane
    - Others DOF tele-operated
  - [Nakadate11 - Waseda Univ.]
    - PBVS, 1 dof




- Renal stone motion tracking
  - [Lee07 - Univ. of Tokyo]
    - 2 orthogonal images
    - PBVS, 3 dof




- Positioning on anatomical section
  - *[Krupa05, Bachta06, Mebarki08, Nadeau10, Li12,…]*, IBVS, 6 dof

- Motion compensation
  - *[Krupa07, Nadeau11, Lee11,…]*, IBVS, PBVS, 6 dof

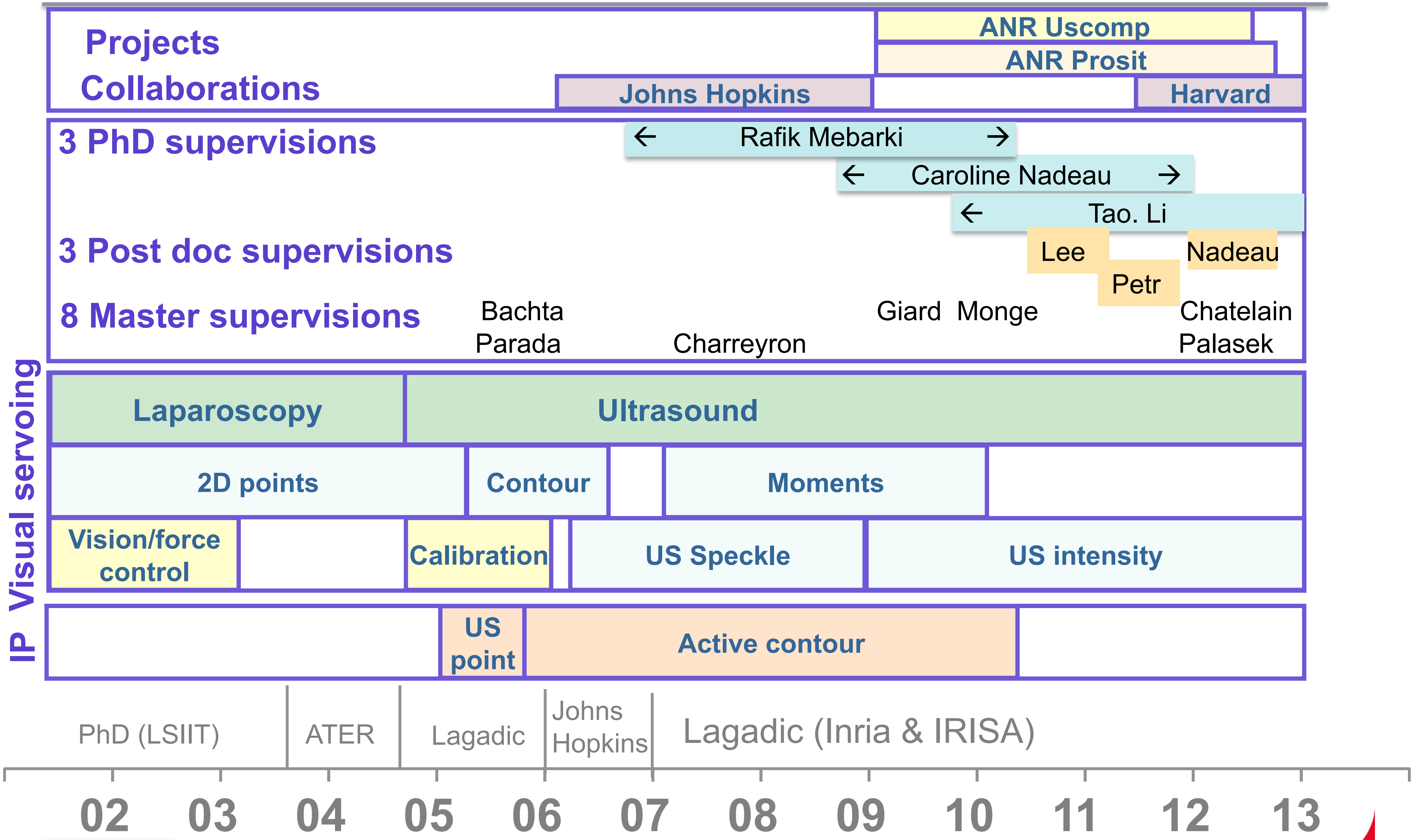
# Contribution overview

- Goal: Generic solutions for eye-in-hand ultrasound visual servoing

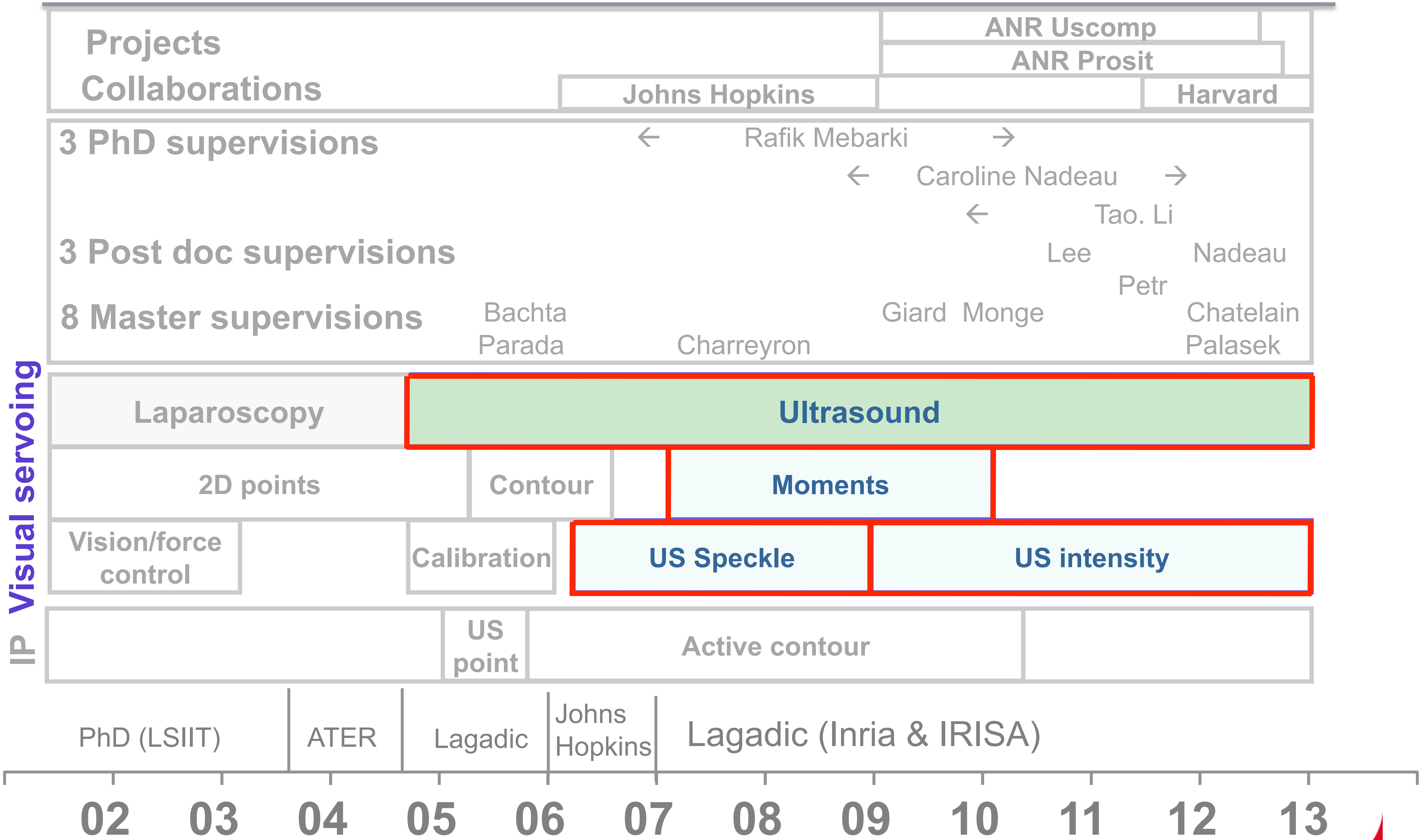
- Issues:
  - Probe interaction with anatomical elements instead of instruments
  - Both in-plane and out-of-plane motion control
  - Extraction of relevant visual information: low image quality
  - Real-time: constrained complexity
  - Physiological motions

- Two main approaches:
  - Geometrical information
    - Image points, contours, 2D moments
  - Dense information
    - Speckle correlation, US image intensity

# Chronology of research works



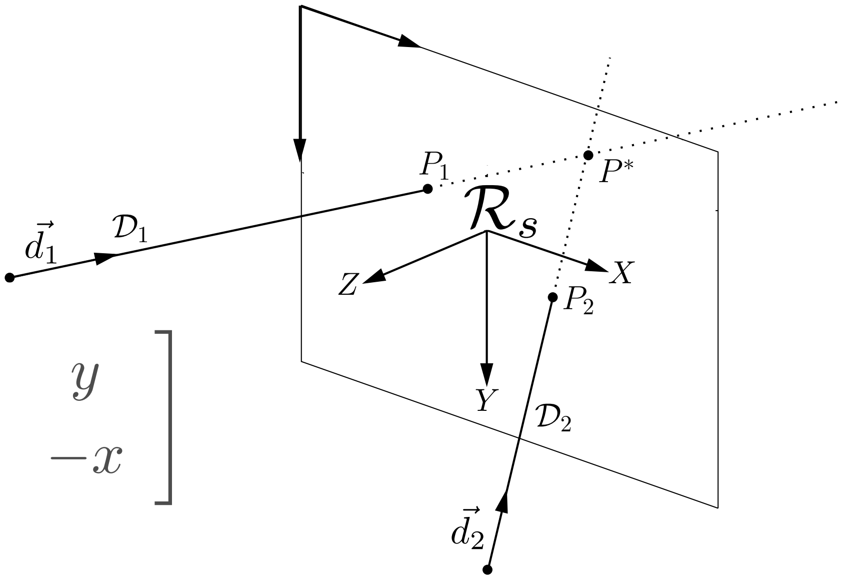
# Chronology of research works



# Outline

- US based visual servoing issues and contribution overview
- Part I: Approaches based on geometrical visual information
  - Image points
  - Image moments
  - Multi-plane approach based on moments
  - Assistance tasks during tele-echography
- Part II: Approaches based on dense visual information

## Part I – The simplest visual feature: image point




- Straight line interaction with US plane
  - Image point $\mathbf{s} = (x, y)$
  - Interaction matrix

$$\mathbf{L_s} = \begin{bmatrix} -1 & 0 & \frac{d_x}{d_z} & \frac{d_x}{d_z}y & -\frac{d_x}{d_z}x & y \\ 0 & -1 & \frac{d_y}{d_z} & \frac{d_y}{d_z}y & -\frac{d_y}{d_z}x & -x \end{bmatrix}$$

- Out-of-plane visual servoing
  - Automatic calibration procedure

*[IROS'05,ICRA'06, Advanced robotics'06]*

# Part I – Image 2D moments: modeling

- Moments of observed cross-section as visual features *- Rafik Mebarki PhD*
  - Generic 2D visual features (area, gravity center, main orientation, etc…)
  - Extraction by active contours based on Fourier descriptors *[ICIP'11, Li]*

- Modeling of 6 well decoupled visual features *[TRO'10, Mebarki]*

$$\mathbf{s} = (x_g, y_g, \alpha, \sqrt{a}, \phi_1, \phi_2)$$

$$\mathbf{L_s} = \begin{bmatrix} -1 & 0 & x_{g_{v_z}} & x_{g_{\omega_x}} & x_{g_{\omega_y}} & y_g \\ 0 & -1 & y_{g_{v_z}} & y_{g_{\omega_x}} & y_{g_{\omega_y}} & -x_g \\ 0 & 0 & \alpha_{v_z} & \alpha_{\omega_x} & \alpha_{\omega_y} & -1 \\ 0 & 0 & \frac{a_{v_z}}{2\sqrt{a}} & \frac{a_{\omega_x}}{2\sqrt{a}} & \frac{a_{\omega_y}}{2\sqrt{a}} & 0 \\ 0 & 0 & \phi_{1_{v_z}} & \phi_{1_{\omega_x}} & \phi_{1_{\omega_y}} & 0 \\ 0 & 0 & \phi_{2_{v_z}} & \phi_{2_{\omega_x}} & \phi_{2_{\omega_y}} & 0 \end{bmatrix}$$

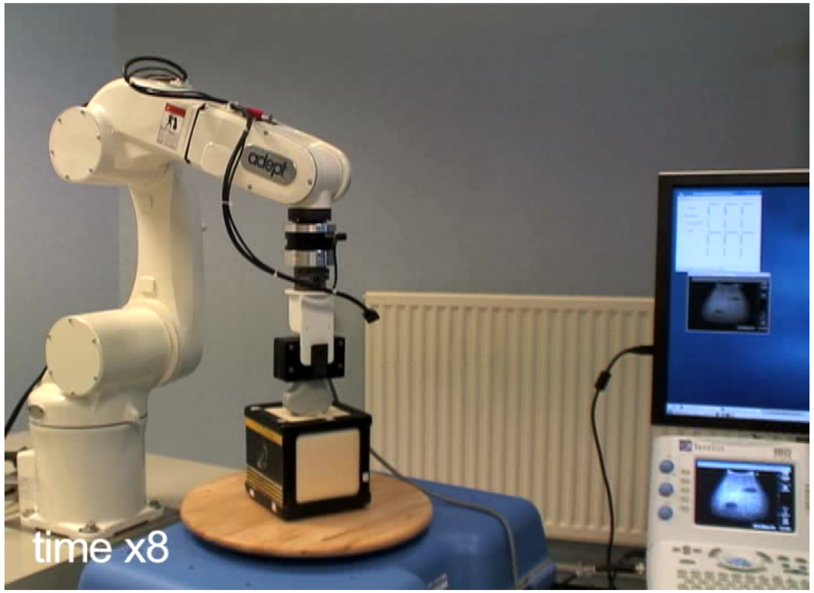
depends on 3D normal vector to the object surface

- derived from pre-operative model *[ICRA'08, MICCAI'08, Mebarki]*
- on-line estimated for unknown object shape *[ICRA'09, Mebarki]*

# Part I – Image 2D moments: Results

- Robotic tasks performed by IBVS

Positioning




Tracking

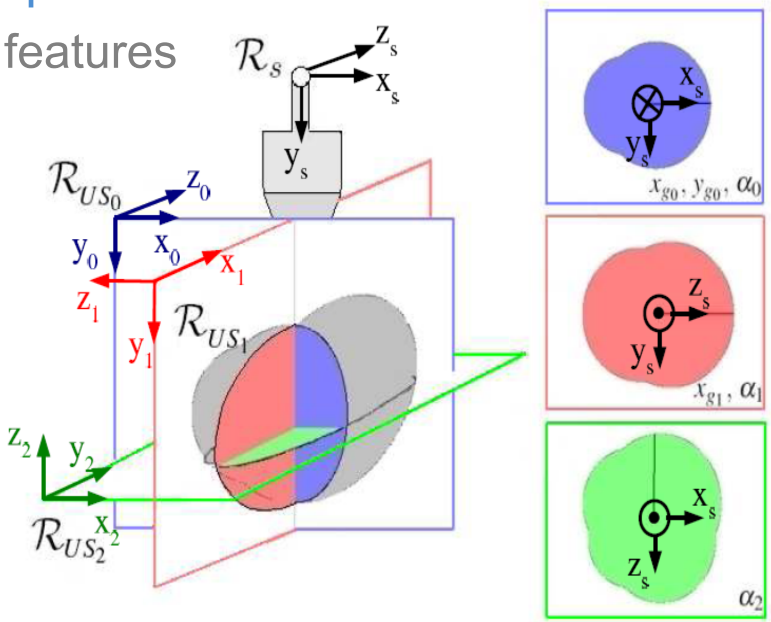
Pro - Needs only a 2D image

- Exponential visual error decreasing

Cons - Possible pose ambiguity (object symmetry, same sections)

## Part I – Multi-plane approach based on 2D moments

- Tri-plane probe - *Caroline Nadeau PhD*
  - Moment based features coupled to in-plane motions
    - Control of in-plane motions: blue plane features
    - Control of out-of-plane motions: additional red and green planes




$$\mathbf{s} = (x_{g_0}, y_{g_0}, x_{g_1}, \alpha_1, \alpha_2, \alpha_0)$$

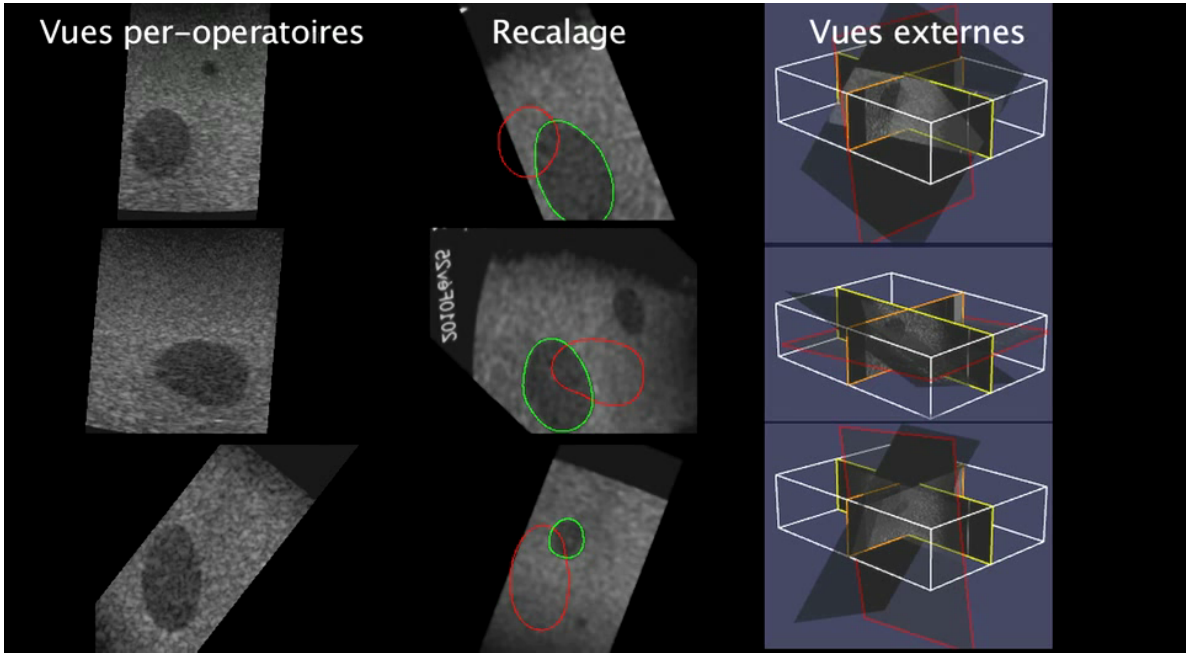
- Approximate interaction matrix

$$\widehat{\mathbf{L}_\mathbf{s}} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & y_{g_0} \\ 0 & -1 & 0 & 0 & 0 & -x_{g_0} \\ 0 & 0 & -1 & -y_{g_1} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

# Part I – Multi-plane approach based on 2D moments

- Probe localization with respect to a 3D pre-operative volume
  *[IROS'10, Nadeau]*

  - Pose computation as a dual problem of visual servoing
  - Control a virtual tri-plane probe to reach 3 orthogonal per-operative images




Pro

- Good pose description from visual features
- No normal vector estimation

Cons

- Needs a 3D probe

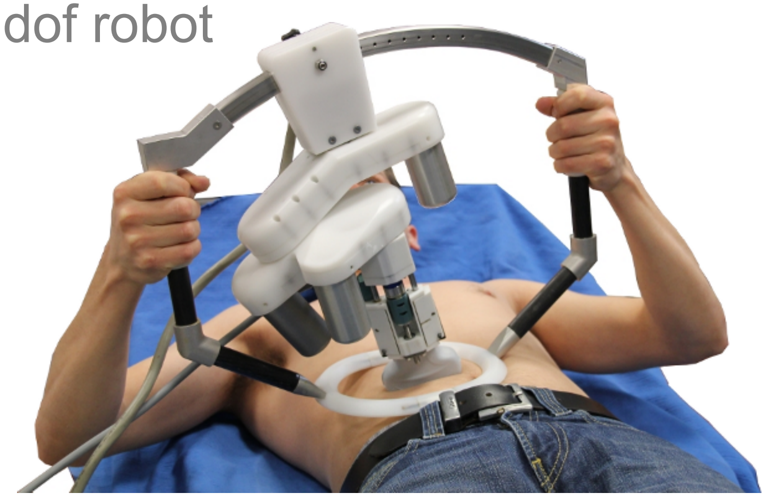
# Outline

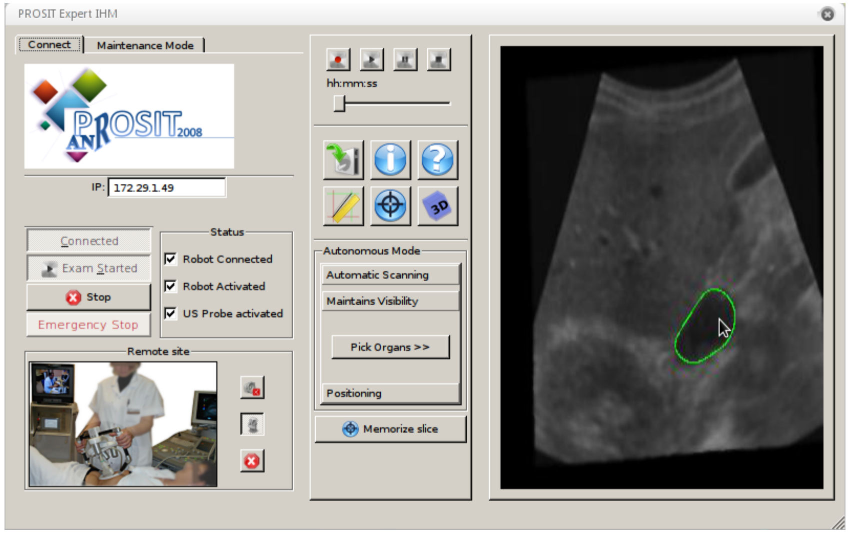
- **US based visual servoing issues and contribution overview**
- **Part I: Approaches based on geometrical visual information**
  - Image points
  - Image 2D moments
  - Multi-plane approach based on 2D moments
  - Real-time contour segmentation
  - Assistance tasks during tele-echography
- **Part II: Approaches based on dense visual information**

# Part I – Assistance tasks during tele-echography

- ANR PROSIT (PRISME, CHU Tours, Inria, Robosoft, Pprime, LIRMM)
  *Tao Li PhD*

- 4 dof robot



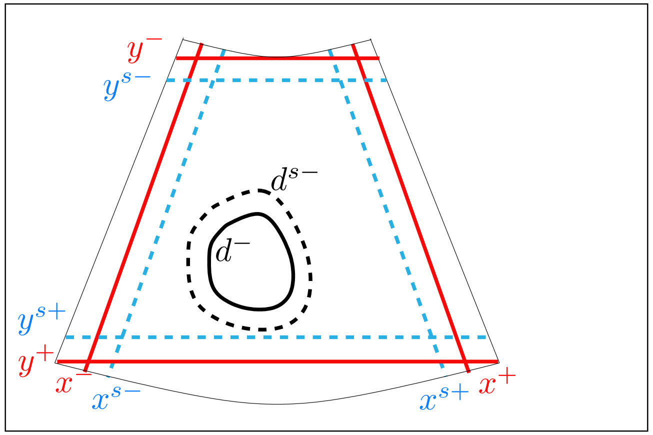



- Automatic retrieval of a desired anatomical section
  - Features computed from moments
  - Desired section recorded during tele-operation phase
  - Replay probe orientation and refine/maintain section by IBVS

# Part I – Assistance tasks during tele-echography

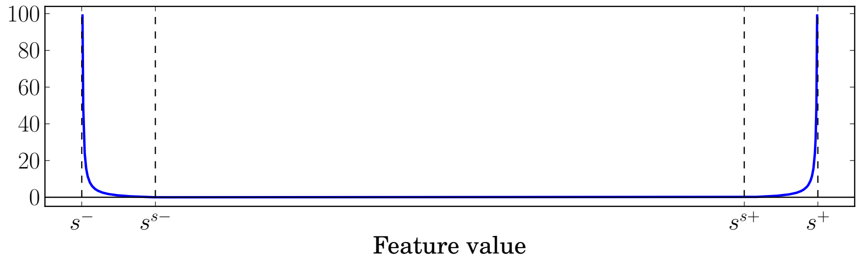
- Maintaining visibility constraints by US IBVS during tele-op *[ICRA'12, Li]*

  - Ultrasound visibility constraints
    - Features computed from moments




  - Fusing visibility with tele-operation control

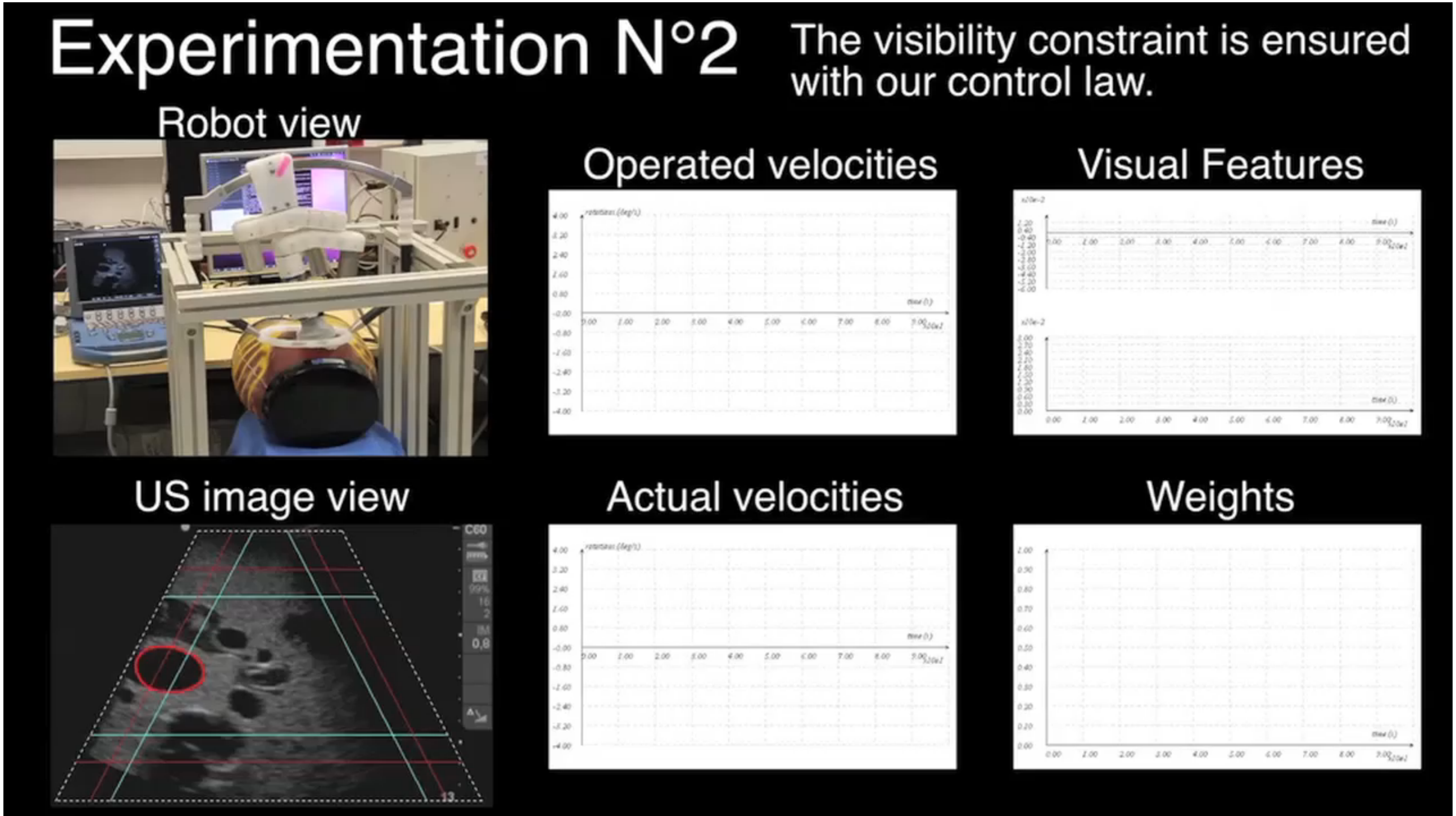
$$\omega = -\lambda(\mathbf{H}\widehat{\mathbf{L}_{\mathbf{s}}})^{+}\mathbf{H}\,(\mathbf{s}-\mathbf{s}^{*}) + \mathbf{P}\omega_{m}$$




    - Visual servoing activated by weighting matrix $\mathbf{H} = \mathrm{diag}(h_x, h_y, h_d)$
    - User can still tele-operate DOF not required from visibility task

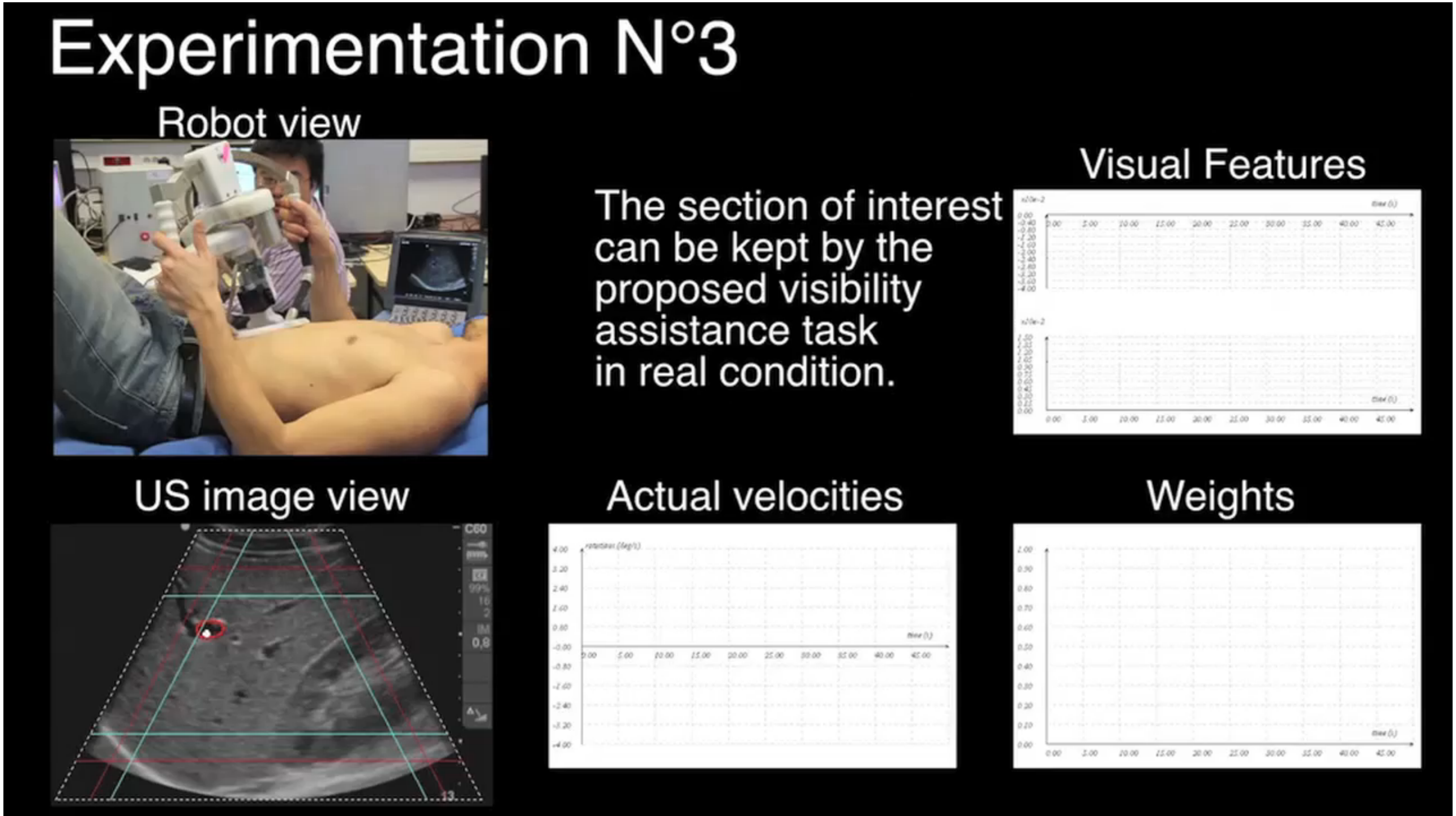
# Part I – Robotic tele-echography assistance tasks

- Maintaining visibility constraints by US IBVS during tele-operation



# Part I – Robotic tele-echography assistance tasks

- Method also compensates patient motion



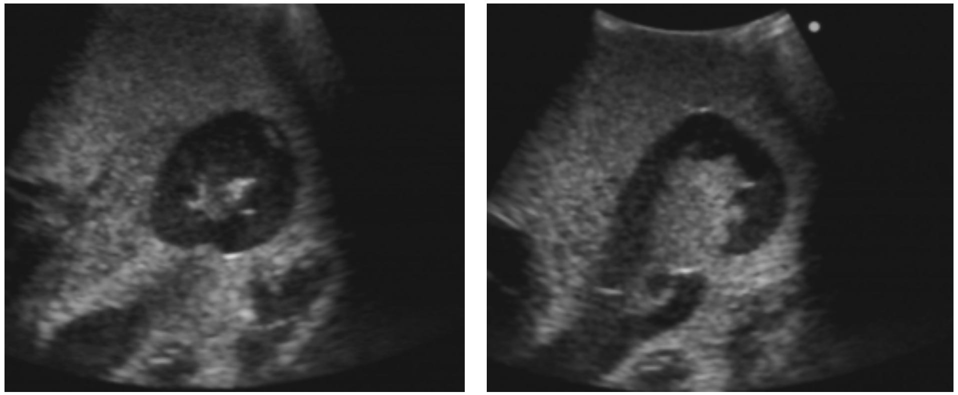
# Outline

- US based visual servoing issues and contribution overview
- Part I: Approaches based on geometrical visual information
- **Part II: Approaches based on dense visual information**
  - Speckle correlation
  - Ultrasound intensity
  - Target motion compensation
  - Target tracking in 3D US volumes
  - Soft tissue deformation tracking

# Main advantages of dense-based approaches

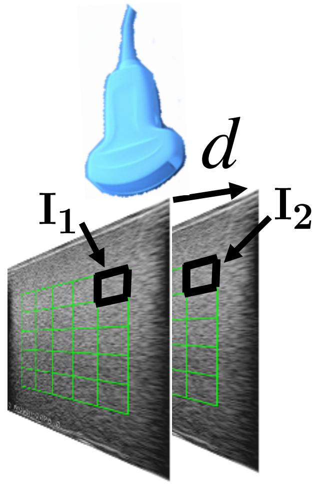
- Less or no image processing
  - Segmentation not required

- Suitable for US images exhibiting
  - Structures hard to detect
  - Topology changes due to out-of-plane motion



kidney successive sections

# Part II – Visual servoing from speckle correlation

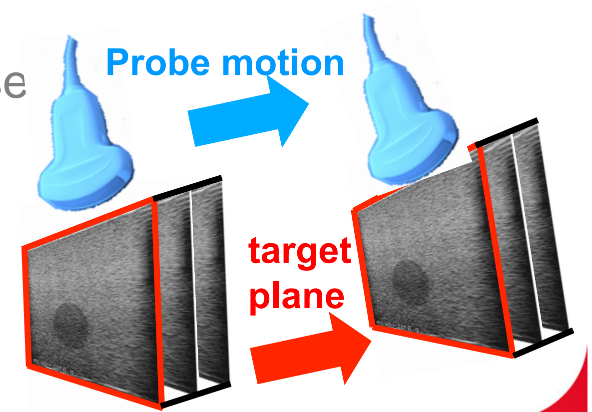



- Objective: compensation of tissue rigid motion
  with Johns Hopkins University *[ICRA'07,MICCAI'07,IJRR'09]*

- Speckle in not a noise
  - Correlation model

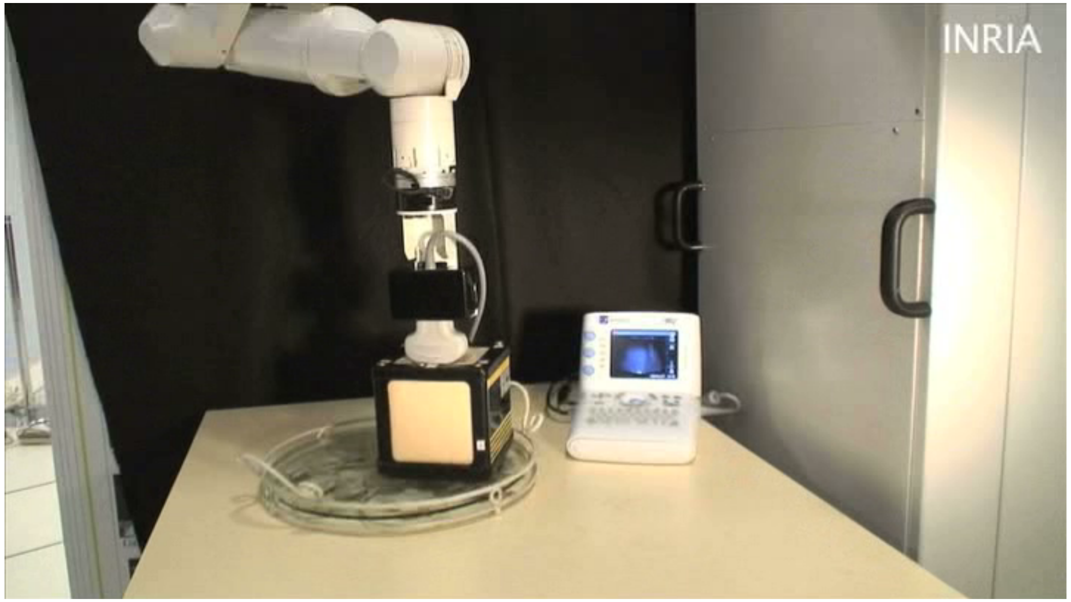
$$\rho(\mathbf{I_1},\mathbf{I_2}) = \exp(\frac{-d^2}{2\sigma^2})$$

- Principle
  - Out-of-plane motion estimations: speckle decorrelation technique
  - In-plane motion estimations: image template tracking [Hager98]
  - Hybrid visual servoing scheme to minimize relative pose between target and observed planes



# Part II – Visual servoing from speckle correlation

- 6 dof rigid motion compensation



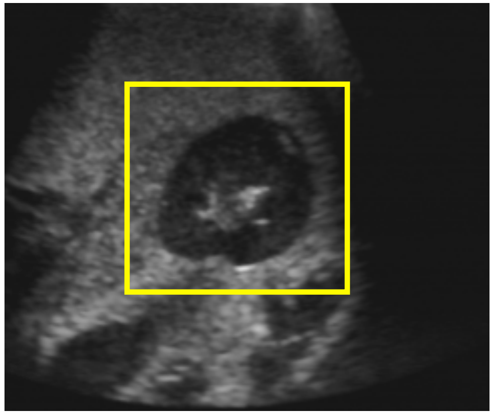

Pro - No segmentation
- Needs only fully developed US speckle
- No structured images required

Cons - Only for motion compensation tasks (not for positioning)

# Part II – Direct intensity-based VS

- Intensity based control
  - Image intensity directly used as input of the control scheme [Collewet11]

- Extension to US B-mode image - *Caroline Nadeau PhD*
  - Assumptions: ultrasound reflected by a physical point is constant & invariant to transducer incidence angle
- Visual features $\mathbf{s}(\mathbf{r}) = (\ldots, I_{u,v}, \ldots)$
- Visual error vector $\mathbf{e}(\mathbf{r}) = \mathbf{s}(\mathbf{r}) - \mathbf{s}^* = \mathbf{I}(\mathbf{r}) - \mathbf{I}^*$



- Interaction matrix $\mathbf{L}_I = -\underbrace{\boldsymbol{\nabla}_I}_{\text{3D image gradient}} \underbrace{\mathbf{L}_\mathbf{x}}_{\text{Interaction matrix of a 3D point}}$

$$\boldsymbol{\nabla}_I = \begin{pmatrix} \frac{\partial I}{\partial x} & \frac{\partial I}{\partial y} & \boxed{\frac{\partial I}{\partial z}} \end{pmatrix}^{!}$$

$$\mathbf{L}_\mathbf{x} = \begin{bmatrix} -1 & 0 & 0 & 0 & \mathbf{0} & y \\ 0 & -1 & 0 & \mathbf{0} & 0 & -x \\ 0 & 0 & -1 & -y & x & 0 \end{bmatrix}$$

# Part II – Direct intensity-based VS

- 3D image gradient estimation
  - Off-line: initial procedure *[ICRA'11, Nadeau]*
    - Dedicated spatio-temporal filter
    - Interaction matrix approximated by the desired one

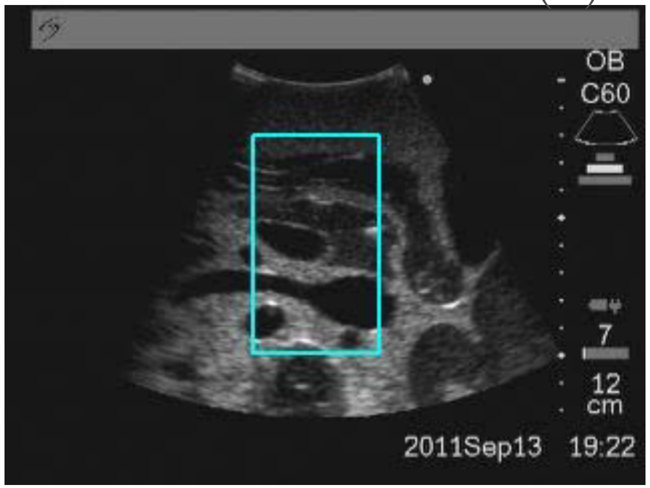
      → for motion compensation tasks
  - On-line
    - From successive images & robot odometry *[IROS'11, Nadeau]*
    - Interaction matrix online updated

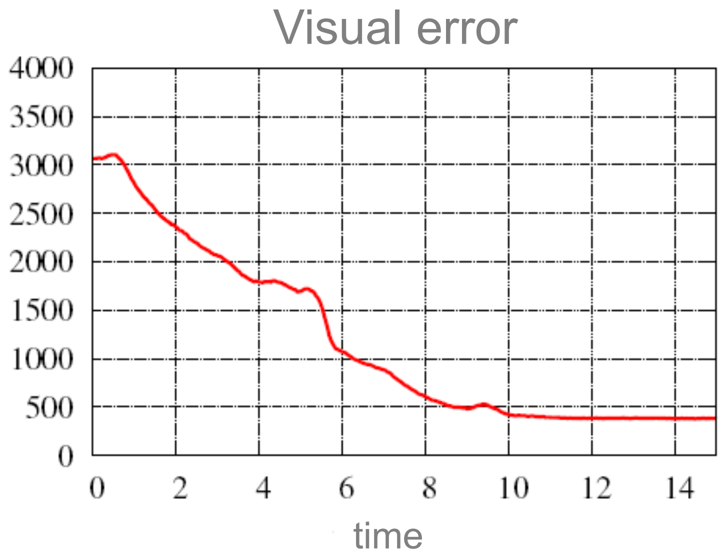
      → for positioning tasks

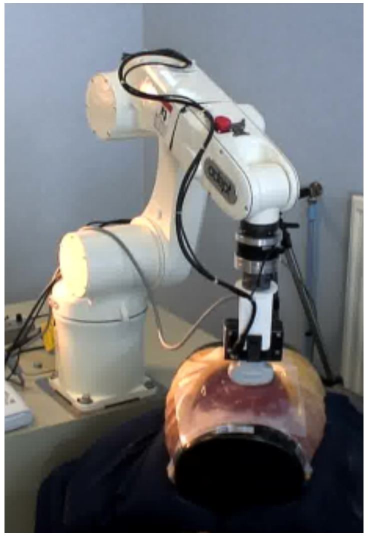
# Part II – Direct intensity-based VS

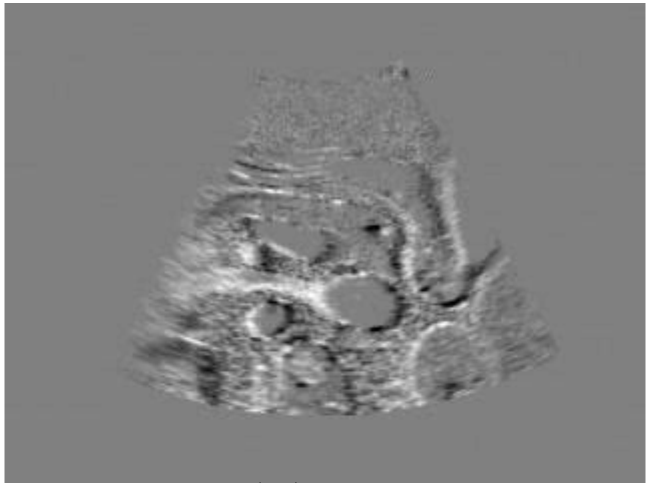
- Positioning task with a 2D probe

$\mathbf{I}(\mathbf{r})$

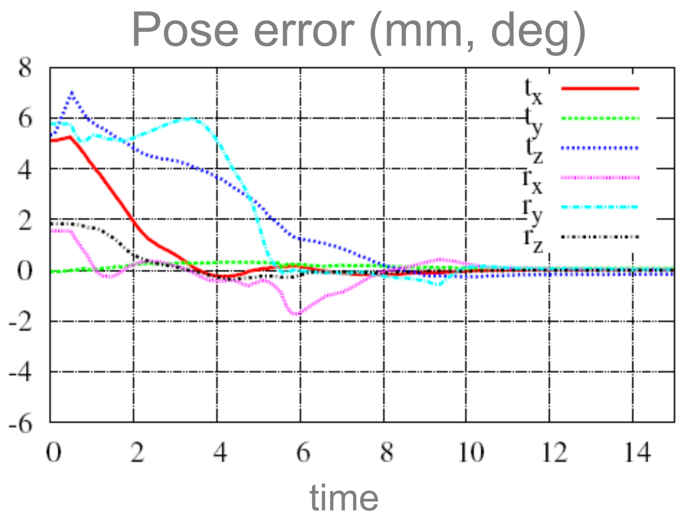


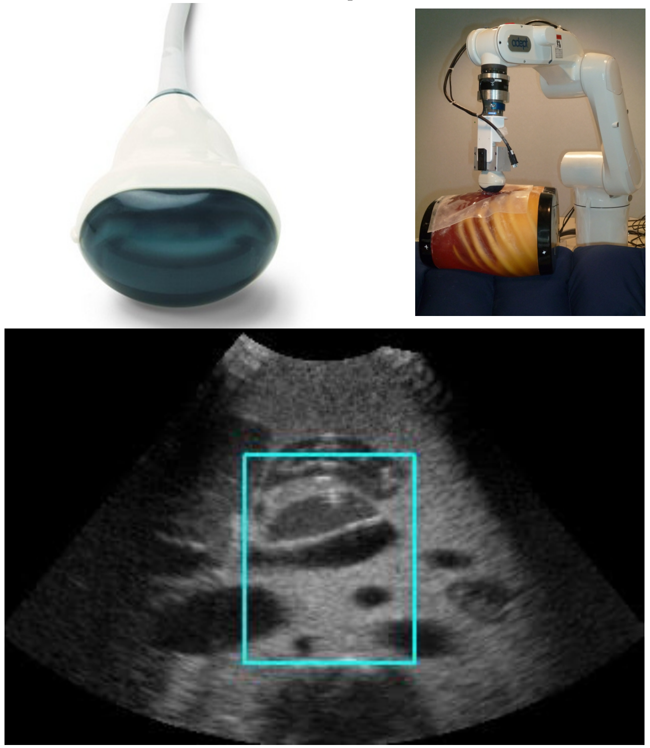


$\mathbf{I}(\mathbf{r}) - \mathbf{I}^*$



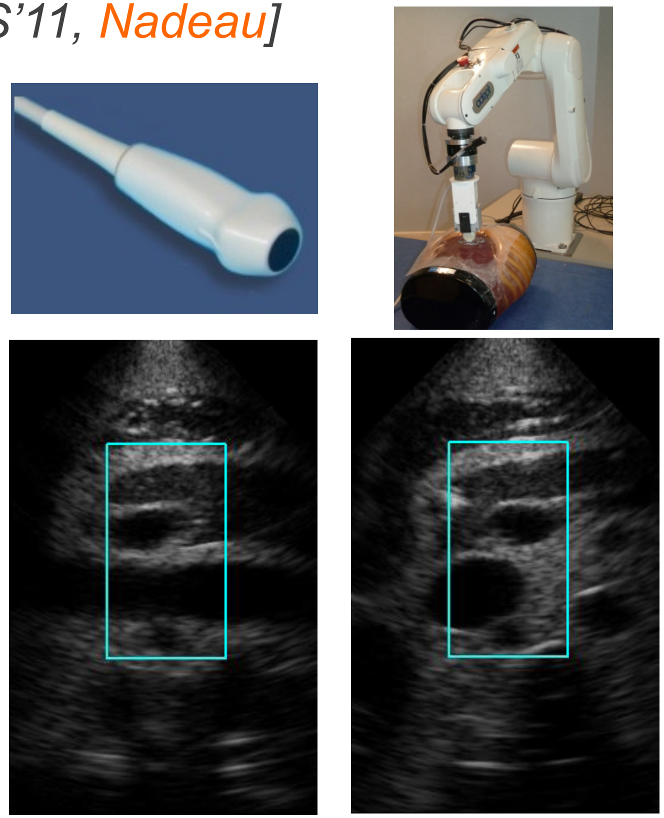
# Part II – Direct intensity-based VS

- Extension to bi-plane and 3D probes *[IROS'11, Nadeau]*



3D probe

- Central 2D images
- 3D gradient directly available from volume



Bi-plane probe

- Two orthogonal 2D images
- 3D gradient estimation

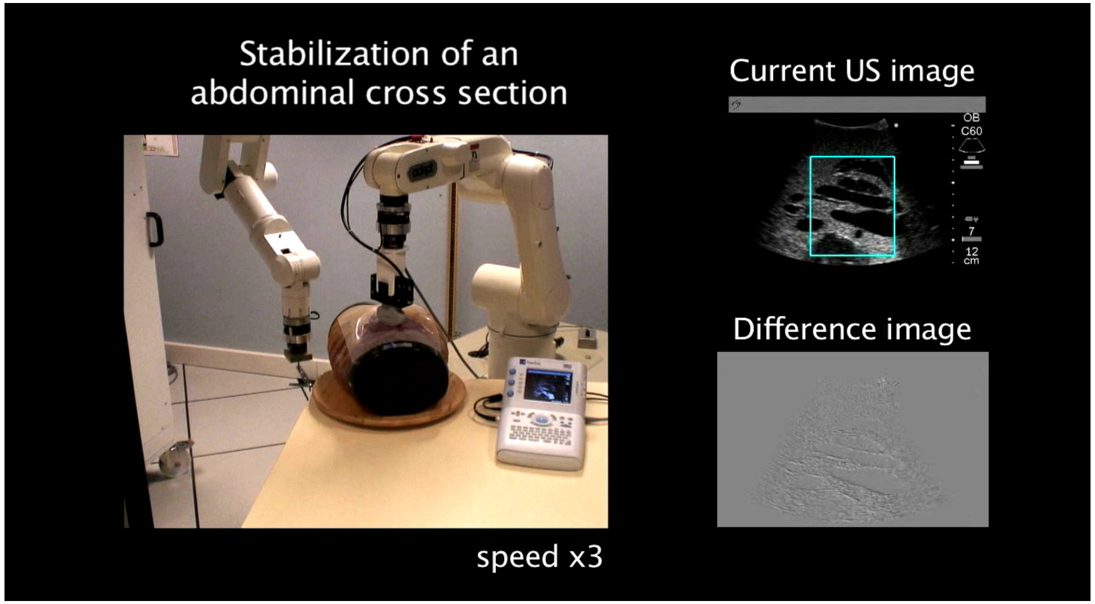
# Outline

- **US based visual servoing issues and contribution overview**
- **Part I: Approaches based on geometrical visual information**
- **Part II: Approaches based on dense visual information**
  - Speckle correlation
  - Ultrasound intensity
  - Target rigid motion compensation
  - Target tracking in 3D US volumes
  - Soft tissue deformation tracking

# Part II – Target rigid motion compensation

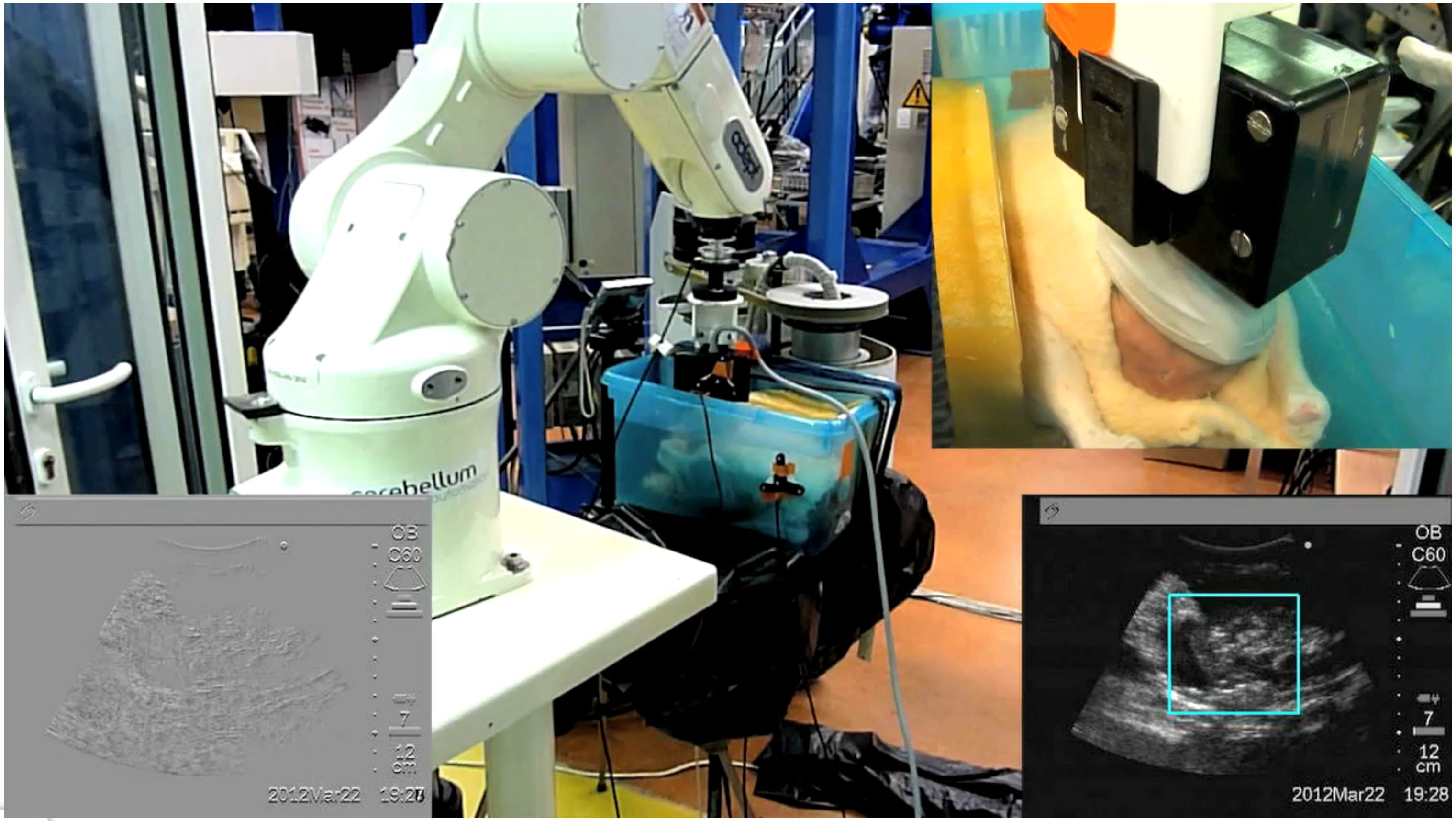
- Context: USComp ANR project (Inria, LIRMM, LSIIT)
- Objective: soft tissue motion compensation during ultrasound imaging
  *[MICCAI'11, Nadeau]*

- Repetitive predictive controller R-GPC [Gangloff06]
  - Organ motion highly correlated with breathing motion
  - Prediction based on constant periodicity of disturbance



# Part II – Target rigid motion compensation

- Ex-vivo results with animal tissue *[Hamlyn Symp. on Medical Robotics'12, Nadeau]*
  - Vision control (5 dof) : Inria (25Hz with 2D probe)
  - Force control (1 dof) : LIRMM (1kHz)
  - Predictive controller R-GPC : LSIIT



# Outline

- **US based visual servoing issues and contribution overview**

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  - Speckle correlation
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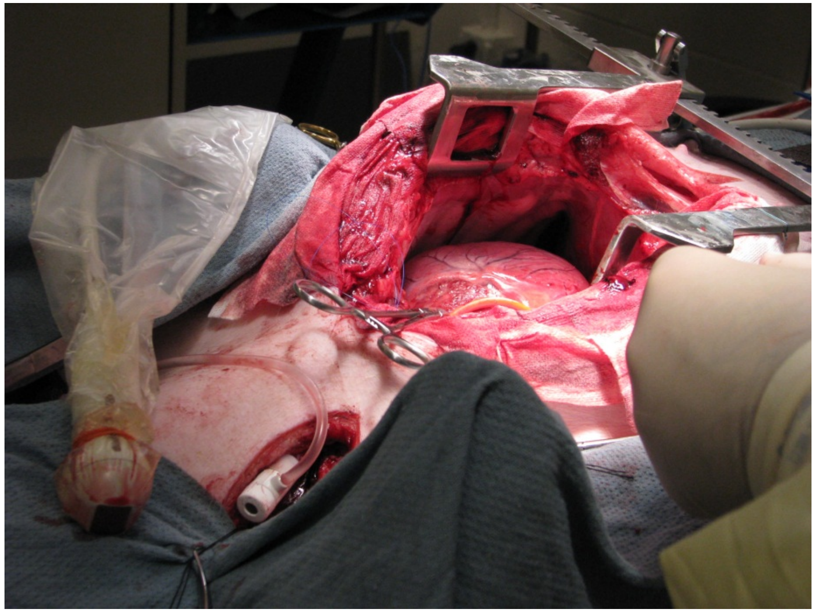


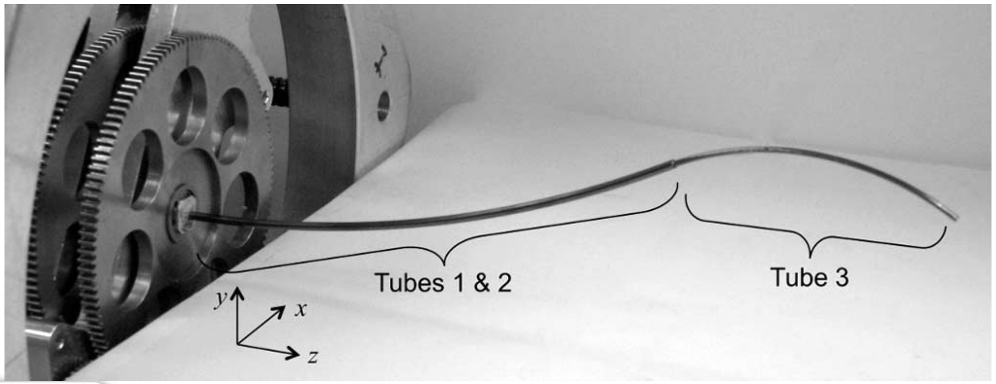
# Part II – Target tracking in 3D US volumes

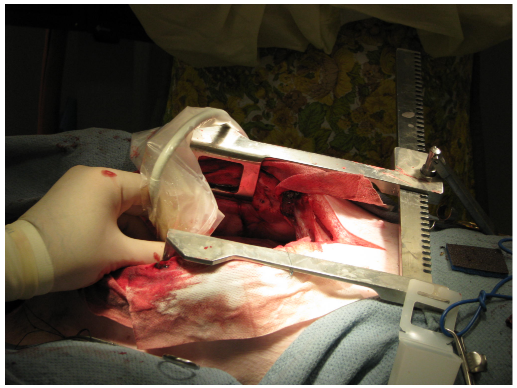
- Objective: Pose computation of a moving target in a sequence of 3D US
  *[Hamlyn Symp. on Medical Robotics'12, Nadeau]*

- Principle: control a virtual 3D probe to stabilize the target image
  - Visual features: voxel intensities of a 3D ROI containing the target

$$\mathbf{s}(\mathbf{r}) = (\ldots, I_{u,v,w}, \ldots)$$

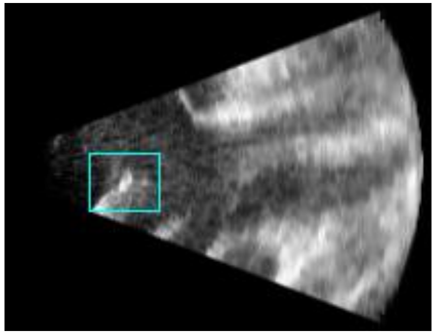
- In vivo experiment on a pig (collab. with Boston Children's Hospital)
  Goal: Tracking the instrument tip of a concentric-tube robot [Dupont10] inserted in a beating heart during cardiac surgery



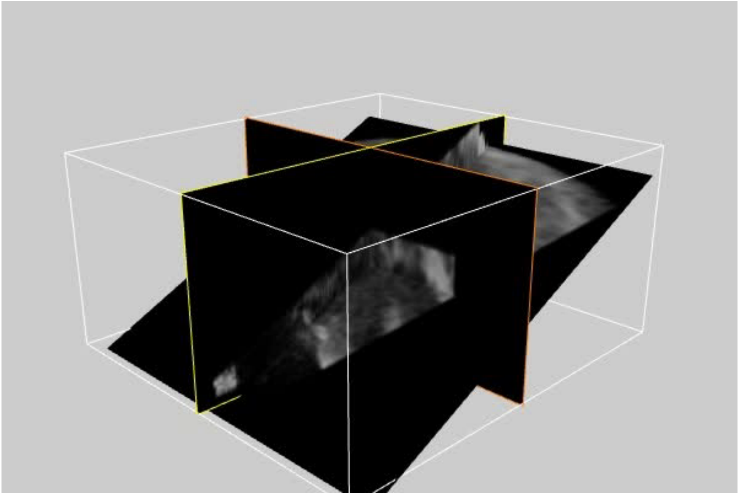



# Part II – Target tracking in 3D US volumes by direct VS

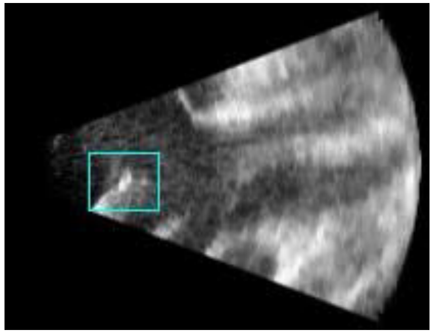
Target to track



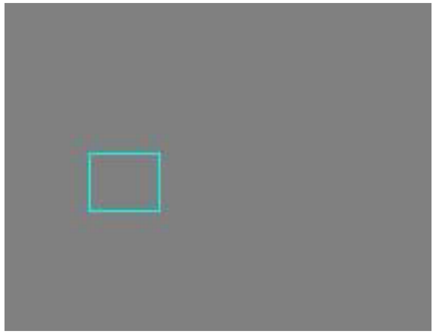
Position of the central image of the virtual probe in the whole volume



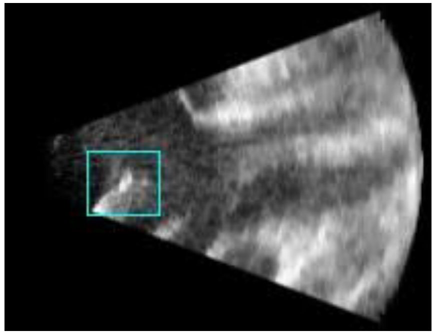
Central image extracted from the volume observed by the virtual 3D probe



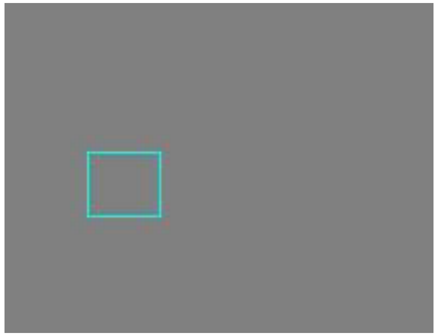
with tracking



$\mathbf{I}(\mathbf{r}) - \mathbf{I}^*$

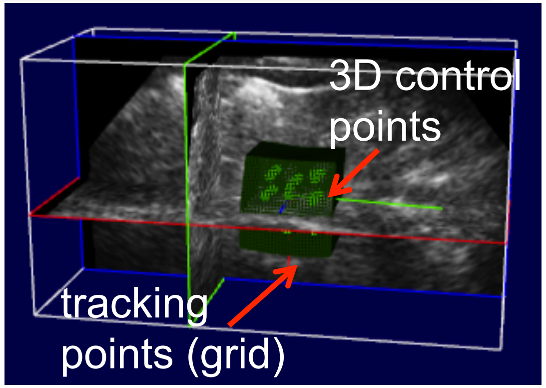


without tracking

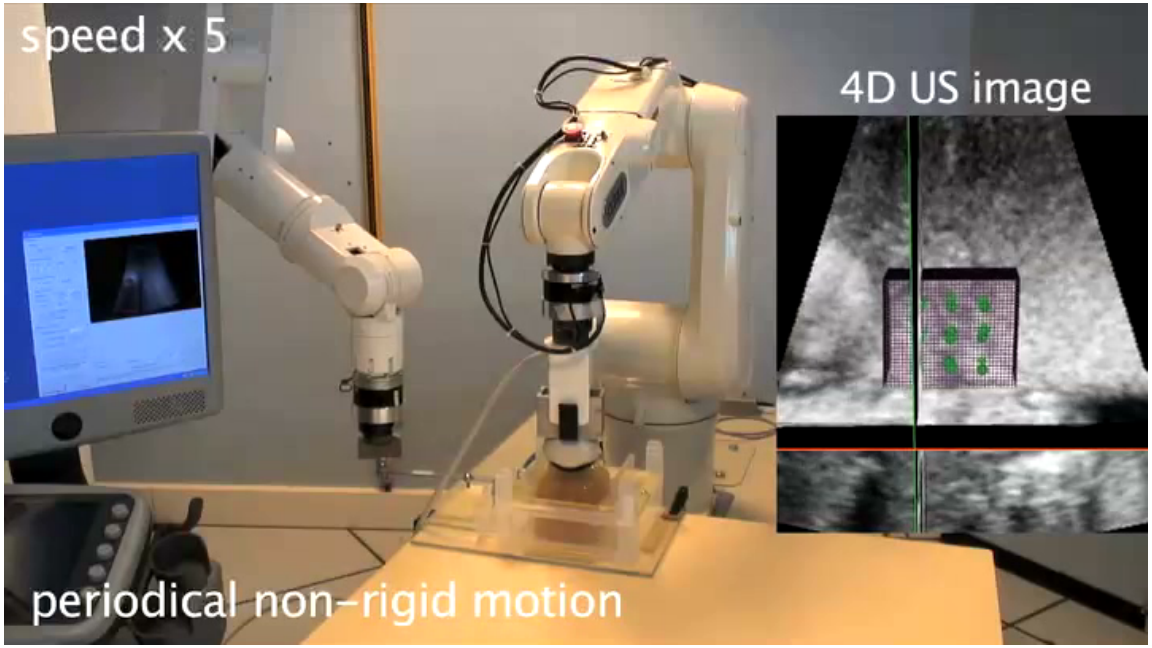


$\mathbf{I}(\mathbf{r}) - \mathbf{I}^*$

# Part II: Soft tissue deformation tracking




- Fast volume reconstruction for 3D motorized probe
- Real-time dense 3D volume tracking *[IROS'11, D. Lee]*
  - Deformation model based on 3D Thin-plate spline
  - Motion parameters: 3D control points
  - Iterative least-square minimization on voxel intensity difference




- Active compensation
  - 6 dof rigid motion extraction
  - Position-based visual servo

# Outline

- US based visual servoing issues and contribution overview
- Part I: Approaches based on geometrical visual information
- Part II: Approaches based on dense visual information
- Conclusion and future works

# Conclusion

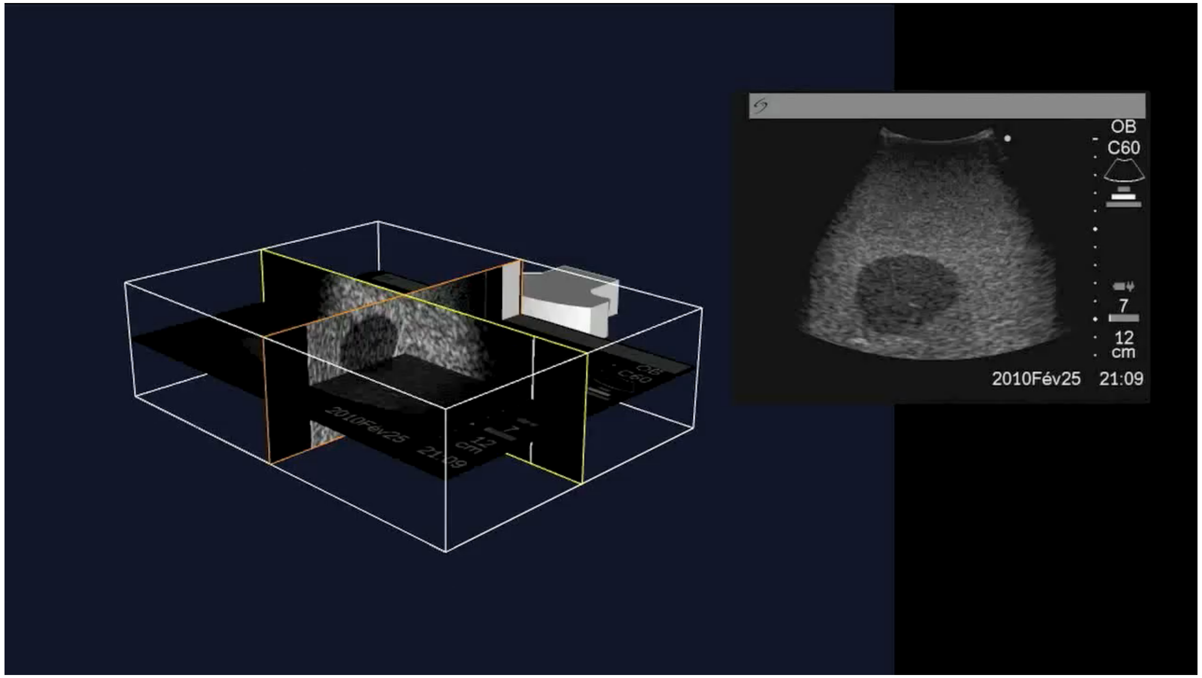
- Generic solutions to control the 6 dof of a robotized probe by ultrasound visual servoing

- Two complementary approaches based on:
  - Geometrical information
    - Suitable for positioning tasks (diagnostic assistance)
  - Dense information
    - No segmentation step required
    - Suitable for tracking tasks (motion compensation)

- Experimental validations of the proposed solutions

# Future works – Soft tissue deformations

- Take into account tissue deformations
  - Dynamic model of organ
  - On-line estimation of deformation parameters

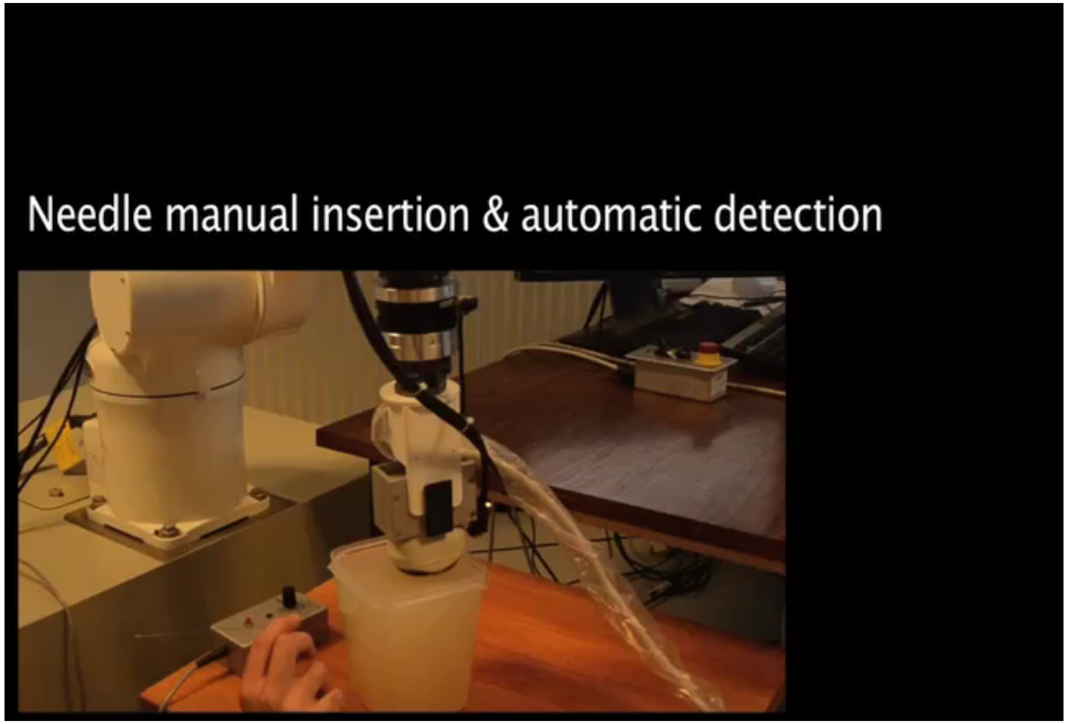



*Software simulator*

# Future works – Multi-robot collaboration with US VS

- Control both the probe and surgical tools by US visual servoing
  - Robot collaboration
  - Generic methods for eye-to-hand US visual servoing
  - Multi-sensor control fusing force and vision
  - Application
    - Automatic flexible needle guidance

      First study (with CHU Rennes)



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