2D and 3d In-Vivo Imaging for Robotic Surgery

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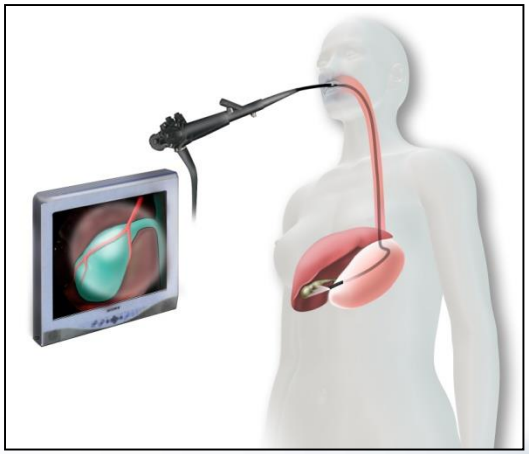
CU Robotics Medical Devices

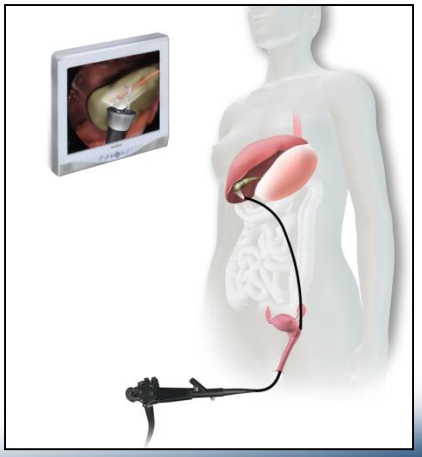
1. In-vivo imaging device (mono)
2. In-vivo imaging device (stereo)
3. Insertable Robotic Effector Platform (IREP)
4. Surgical Structured Light (SSL)

And thanks to many, many collaborators!

Surgical Robotics: Research Goals

- Create simple-to-use and cost-effective surgical robots
- Convert more "major access" operations to "minimal access" operations.
- Reduce the invasiveness of current minimal access interventions
  - SPA: **S**ingle **P**ort **A**ccess for laparoscopic surgery
  - NOTES: **N**atural **O**rifice **T**ranslumenal **E**ndoscopic **S**urgery
  - Use natural body openings with robotic platforms





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U.S. NEWS

Robotic Surgery Brings Higher Costs, More Complications, Study Shows

Columbia Researchers Compared Robotic Surgery to Regular Laparoscopic Surgery for Removing Ovaries, Ovarian Cysts

By MELINDA BECK CONNECT

Updated Oct. 7, 2014 6:53 p.m. ET

Doctors perform a single-site robotic-assisted hysterectomy in Los Angeles in April. *Reuters*

In the latest study to question the value of robotic surgery, researchers from Columbia University found that the technology costs significantly more and has a higher rate of complications than regular minimally invasive surgery for removing ovaries and ovarian cysts.

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Current Generation Robotic Surgery

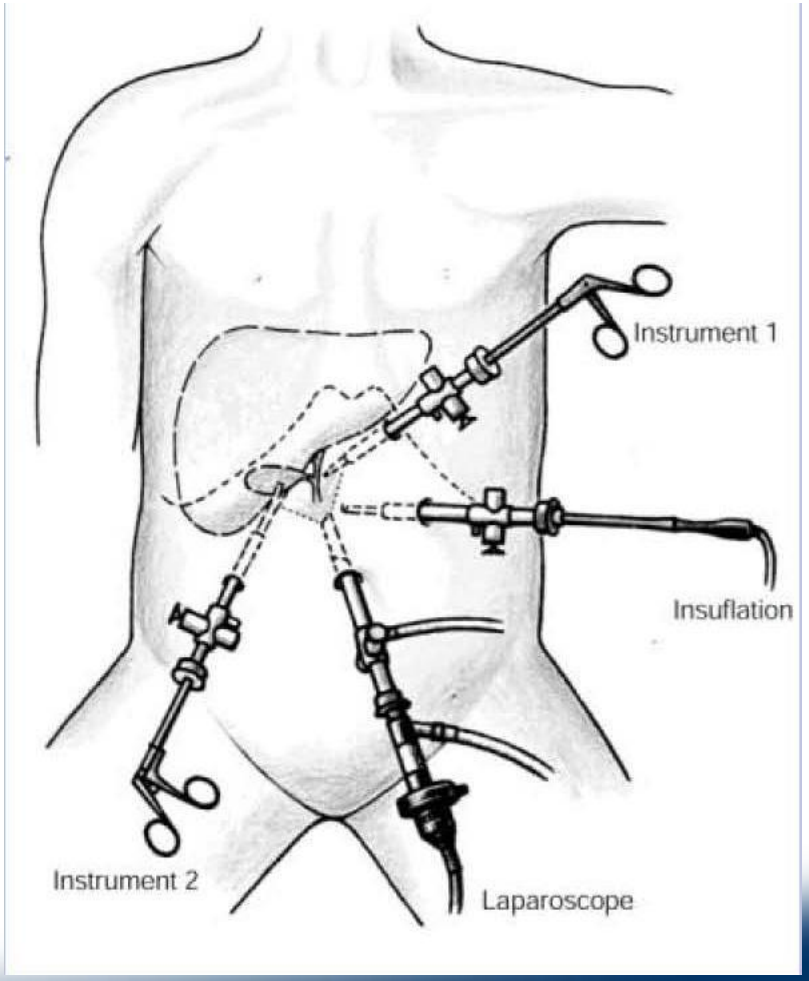
Devices such as DaVinci®
Huge leap in robotics, but:

- Large footprint in the OR
- Cost is extremely high
- Requires multiple incisions
- Multiple assistants needed
- Uses traditional endoscope with limited mobility within body cavity
- Has not reduced the invasiveness of robotic MIS
- While this paradigm has been enormously successful, and has spurred development of new methods and devices, it is **ultimately limiting in what it can achieve**

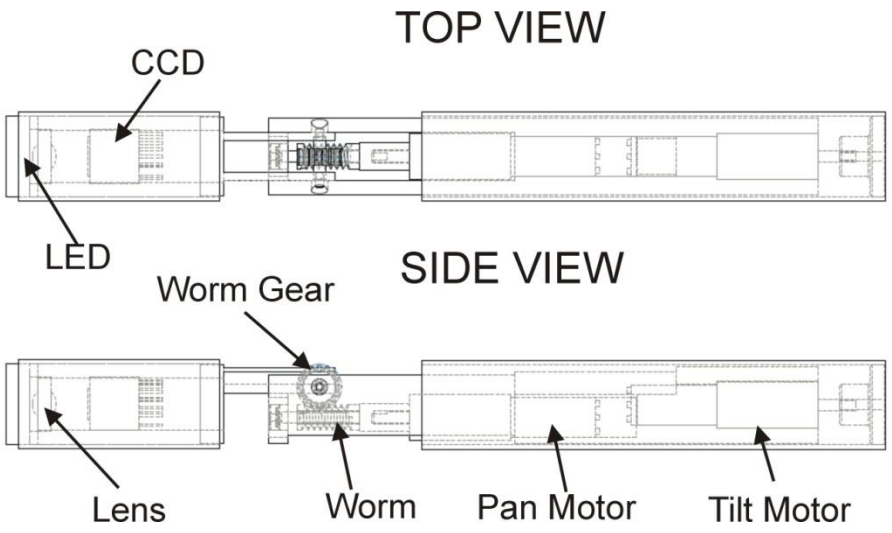
Problems with Current Imaging Devices

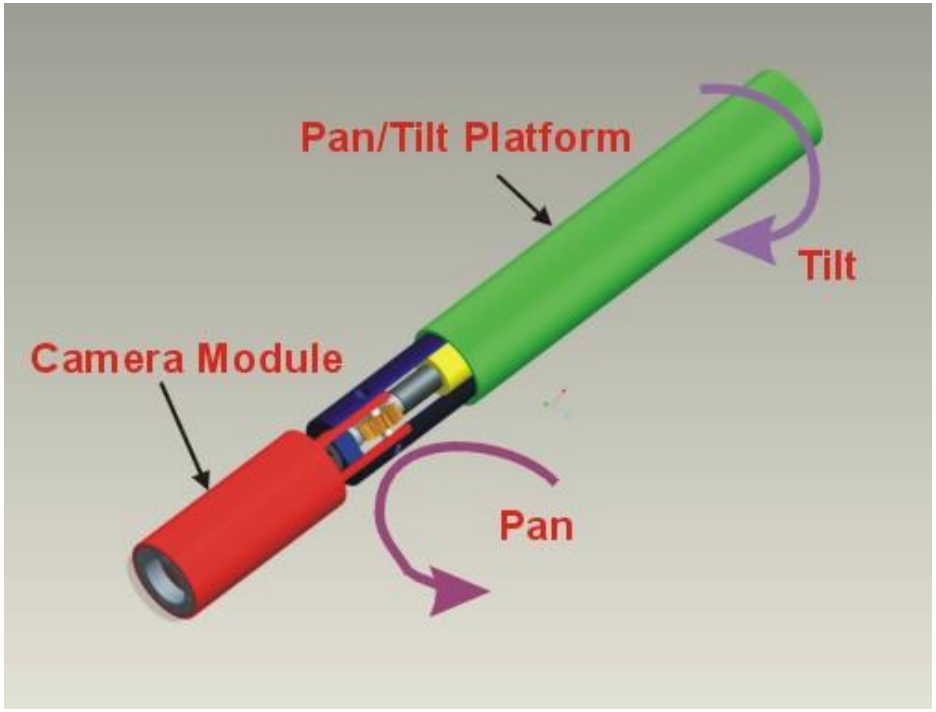
Can we improve on the traditional laparoscope?

- Laparoscope Issues:
  - Narrow angle imaging
  - Limited workspace
  - Multiple incisions for camera placements
  - Counter intuitive motion for control
  - Trained assistants needed to control the camera
  - Multiple incisions for camera placements
  - Additional incisions needed for laparoscopic instruments.



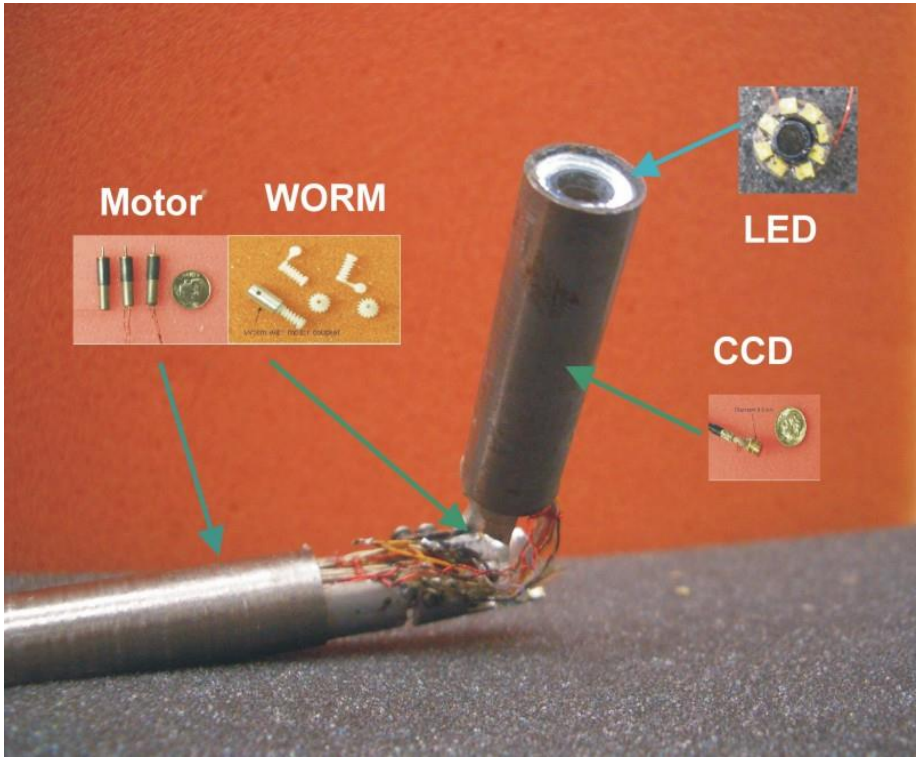
In-Vivo Single Camera





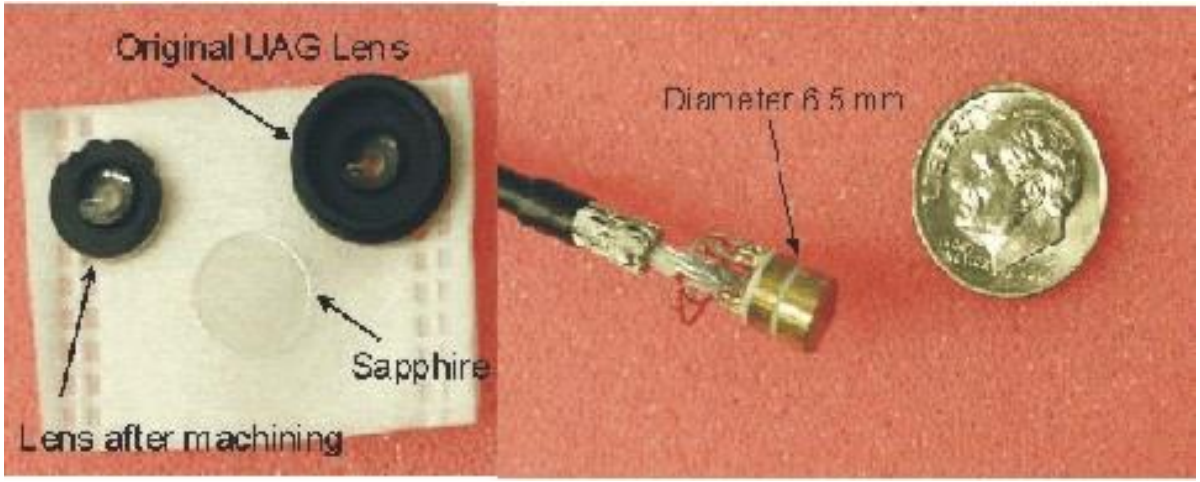
Single Camera*

- 110 mm in length and 11 mm in diameter.
- 130 degree Pan, 90 degree Tilt.
- Integrated 8 LED light source.
- 6.5 mm CCD sensor.
- Fully sealed camera head.
- Joystick control.



*Tie Hu, Peter K. Allen, Nancy Hogle and Dennis Fowler Surgical Imaging Device with Pan, Tilt, Zoom, and Lighting, Intl. Journal of Robotics Research, 2009

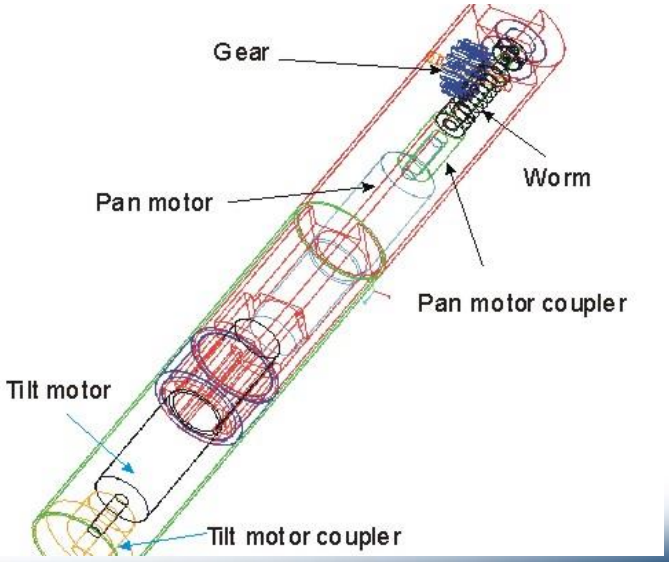
Lens and Camera Unit



- Pin hole lens
  - Focal length 5.0 mm, F number 4.
  - Angle of view D-H-V(85.4-68.3-50.9).
- 6.5 mm CCD camera sensor.
  - 450 TV lines in horizontal resolution and 420 TV lines in vertical resolution.
- Fully sealed package to isolate body fluid and moisture.

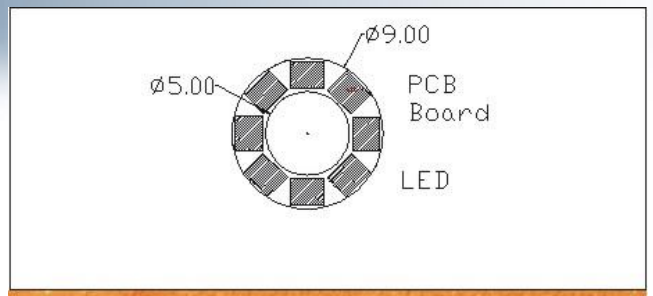
Pan/Tilt Mechanism

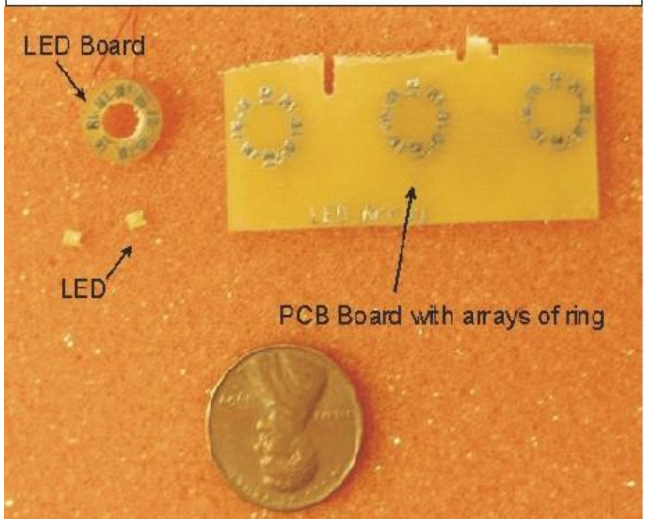
- Miniature Brushless DC motor (0513G, Faulhaber Group).
  - 25mNm torque.
  - 5.8 mm in diameter.
- Miniature worm gear (Kleiss Gear Inc.)
  - gear ratio 16:1.

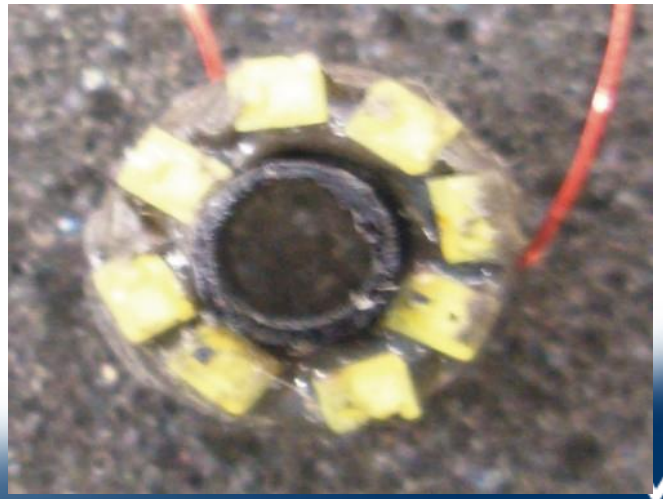


LED Light Source

- Light-emitting diode (LED) as a light source in laparoscopy:
  - Lower power
  - Higher efficiency
  - Compact package
  - Longer lifespan
  - Lower cost
- Luxeon portable PWT white LED(LXCL_PWT1)
  - 2.0 X1.6 X 0.7 mm
  - 26 lumens of light at 350 mA
- 8 PWT LED in a printed circuit board with 9mm diameter.
  - 208 lumens light at 8.4 w







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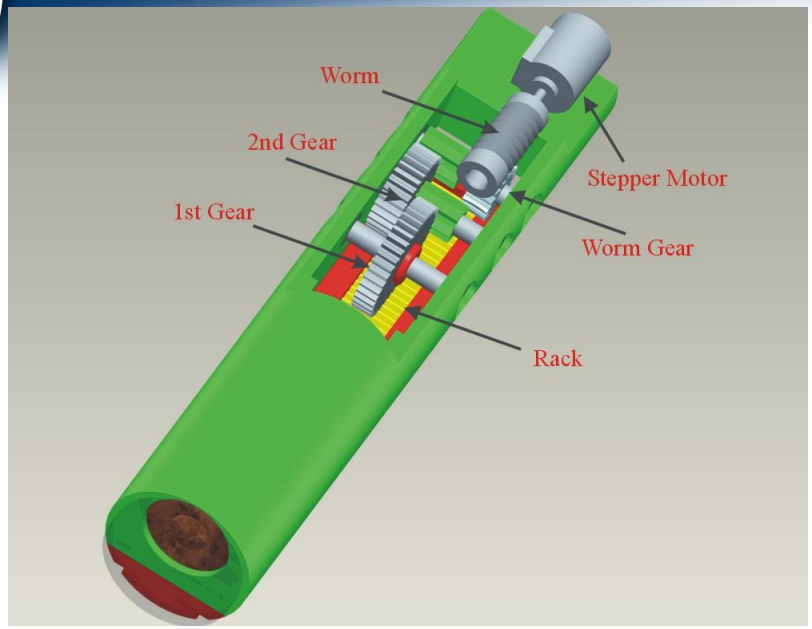
Add Zoom



- Mechanical zoom: linear motion of camera head
- Stepper motor drives rack and pinion mechanism
- Can only achieve ~ 2x zoom

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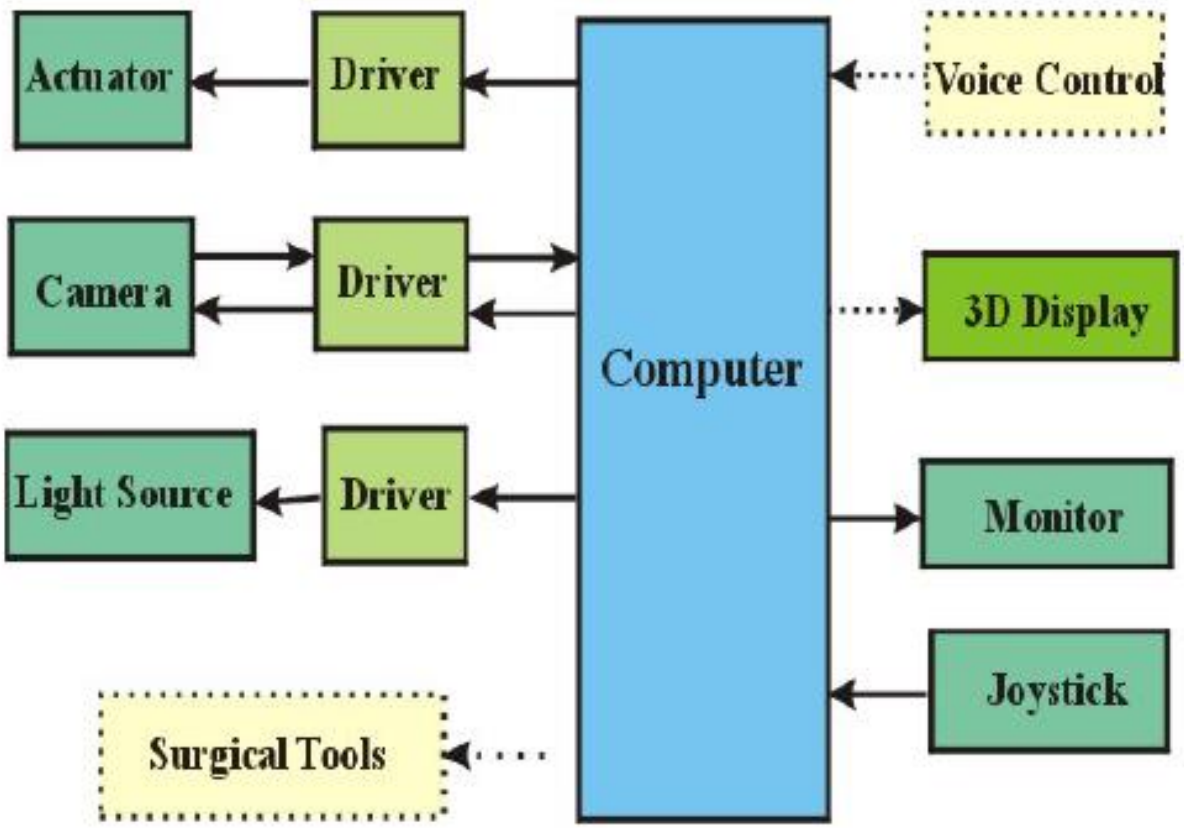
System Architecture



No expensive console needed, just a standard PC!

Mounting the Camera

- Camera attached to insuflated abdominal wall
- Attachment methods:
  - Suturing: small stitch through abdomen
  - Magnets
  - “Fish Hook” which grabs the abdominal wall
  - Intelligent trocar for attachment

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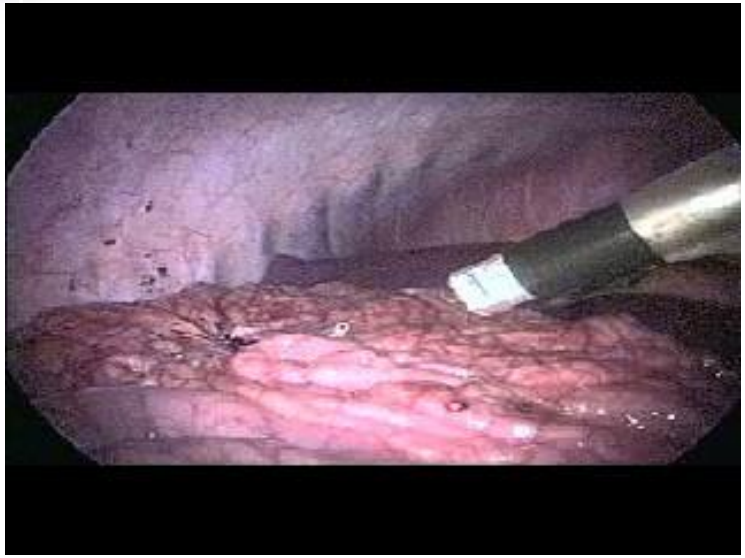
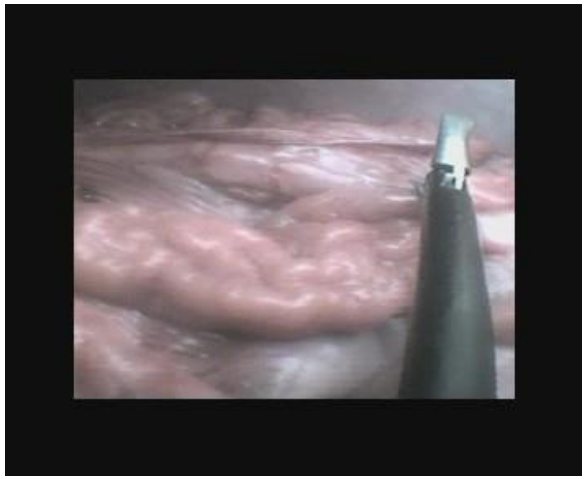
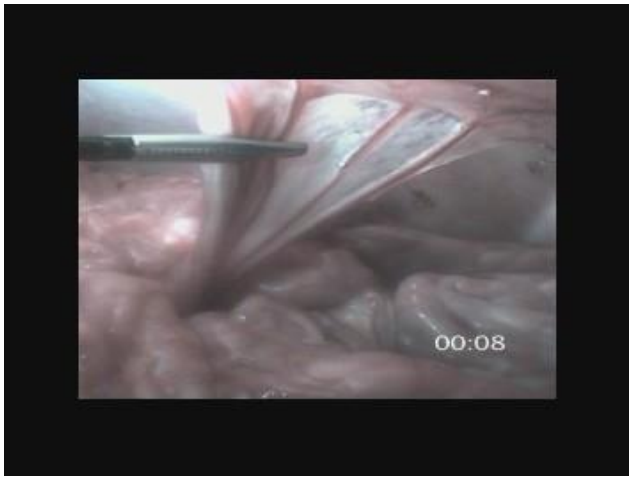
Suturing the Camera



In-Vivo Animal Experiments

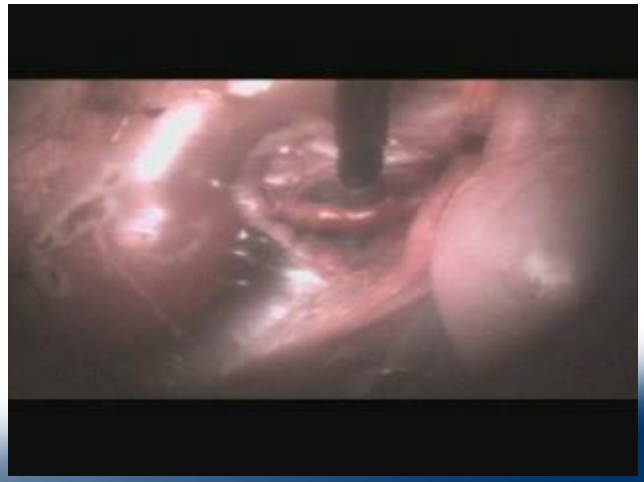


Bowel Running



Appendectomy

Suturing



Nephrectomy

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Insertable Pan/Tilt Endoscope with Integrated Light Source

Intelligent Software

- Position/Velocity control of axes
- Intuitive Joystick Control
- Real-Time Image Processing:
  - Digital Zoom
  - Image rotation/stabilization
  - Distortion Correction
  - Picture-in-Picture
  - Visual Servoing/Tracking
  - 3D Stereo output

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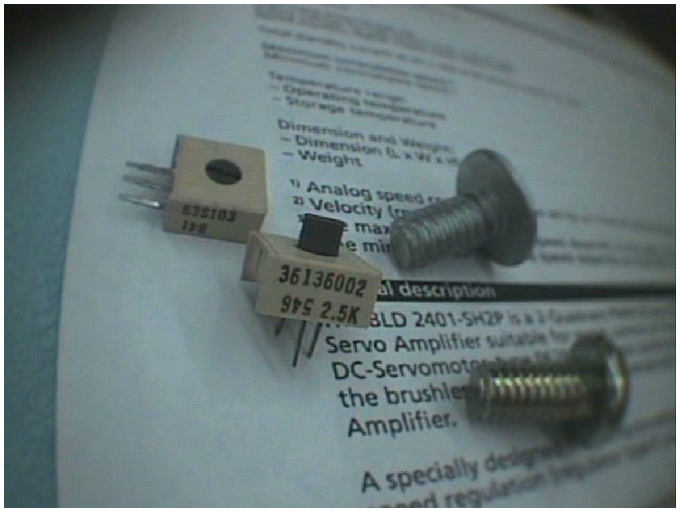
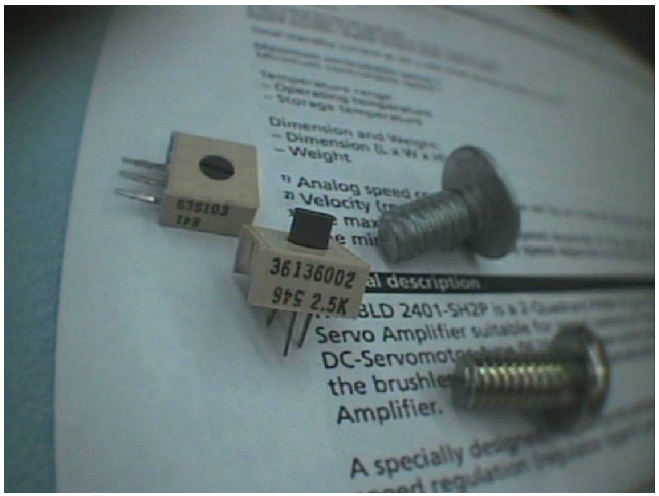
Image Processing

Zoom :

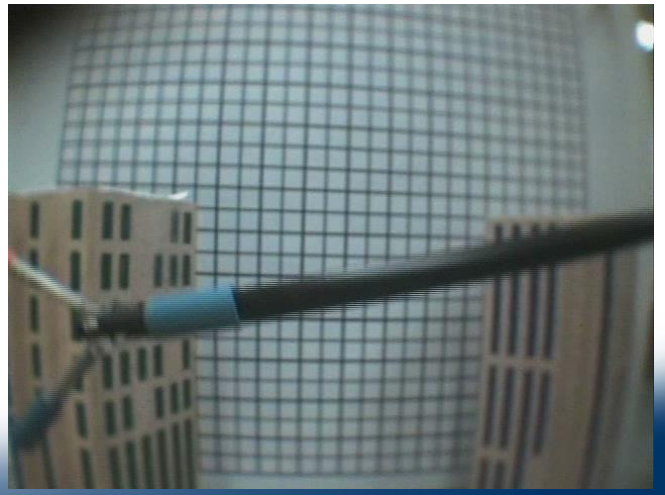


Picture in Picture :



Rotation :

Distortion Correction :



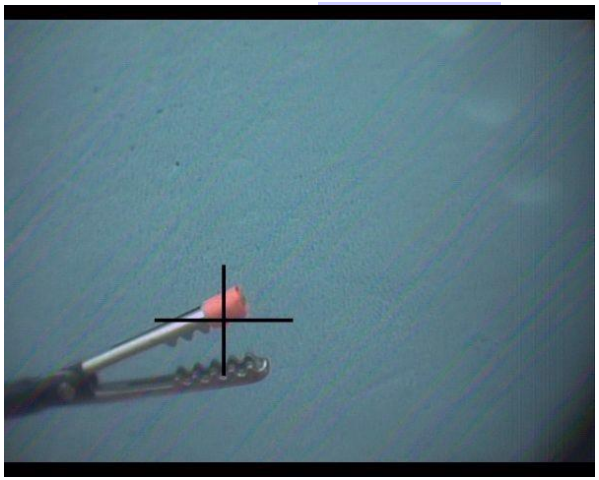
Visual Servoing

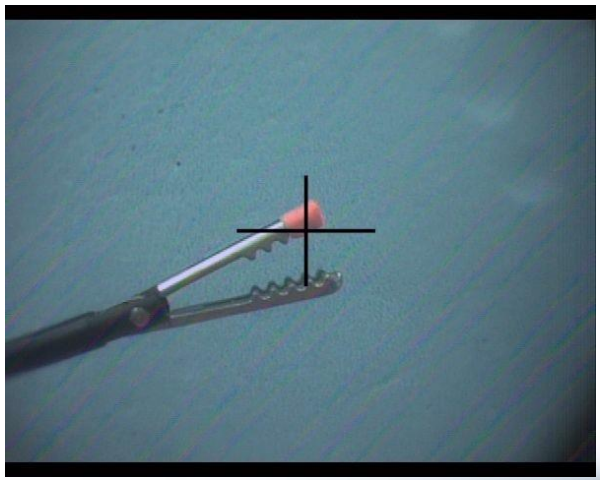
- Allows shared autonomy with surgeon
- The feedback from the tracker can be used to drive motors to keep the tool in the center of the image
- PD controller used
- (E_x , E_y): offset error of tracker from center of image

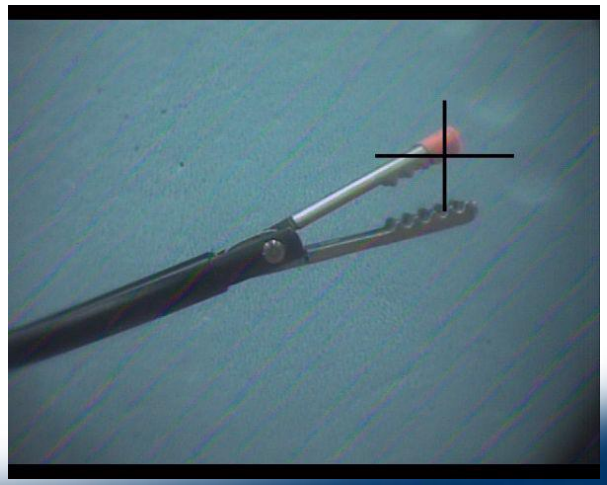
$$\text{Pan speed} \propto (\alpha_x * E_x) - (\beta_x * dE_x/dt)$$

$$\text{Tilt speed} \propto (\alpha_y * E_y) - (\beta_y * dE_y/dt)$$

- Video







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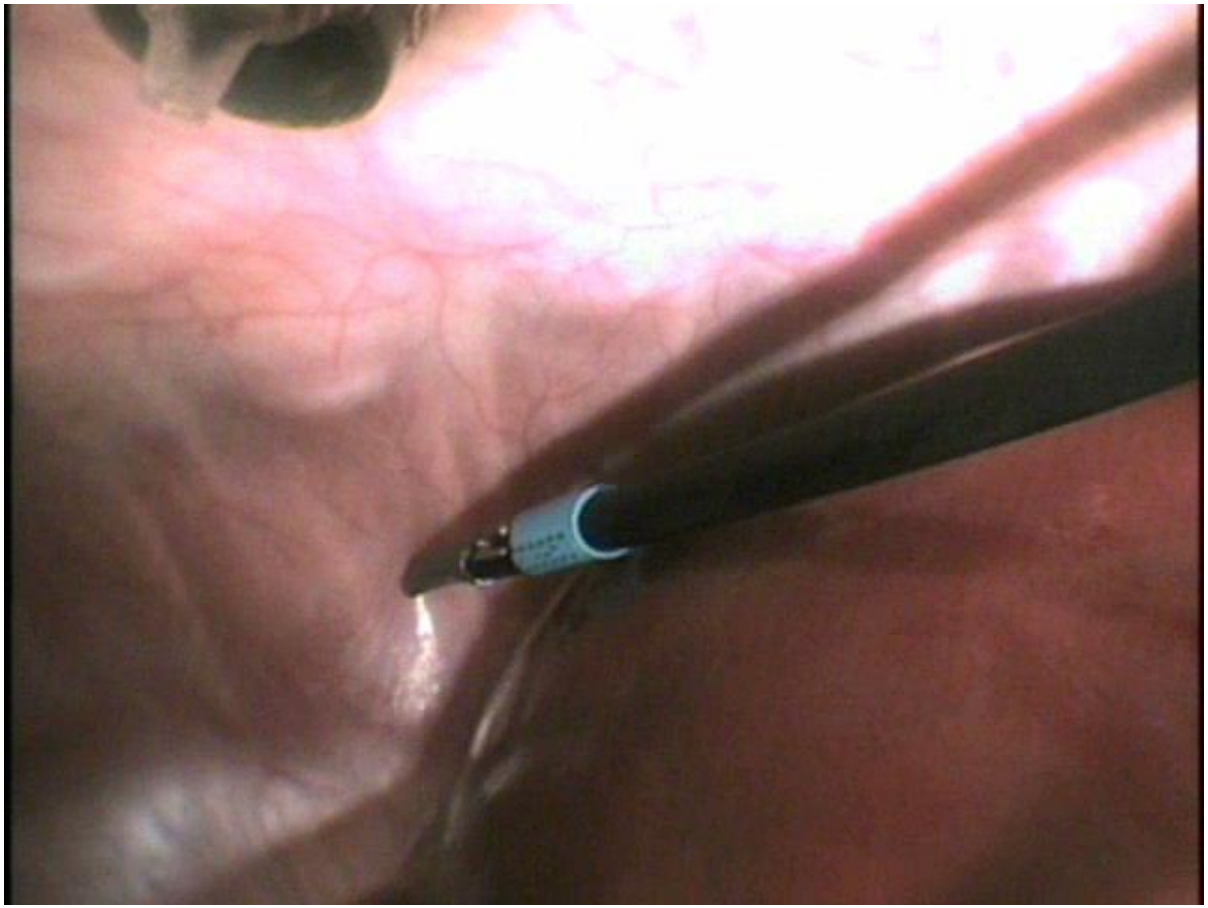
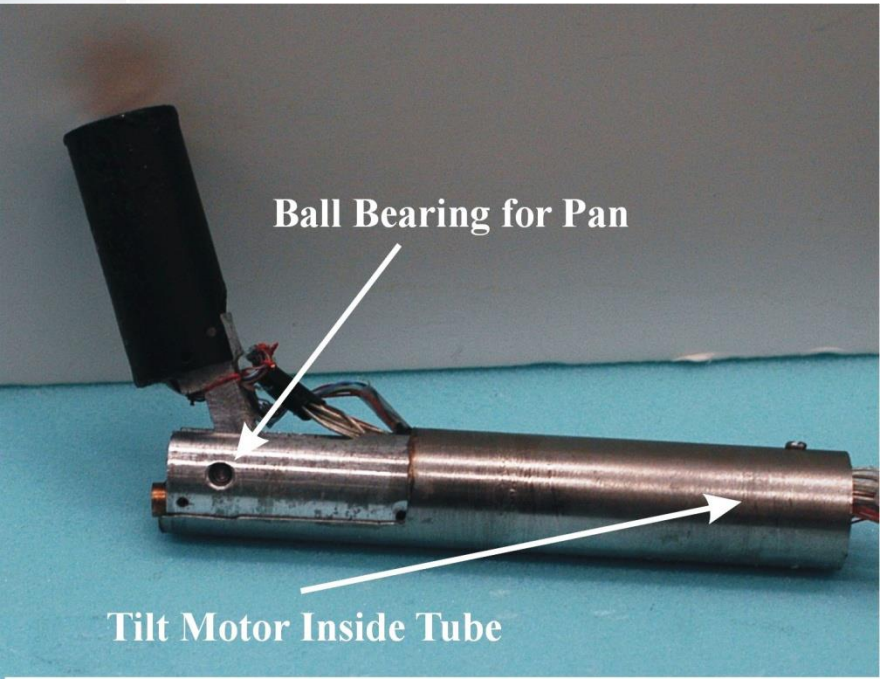
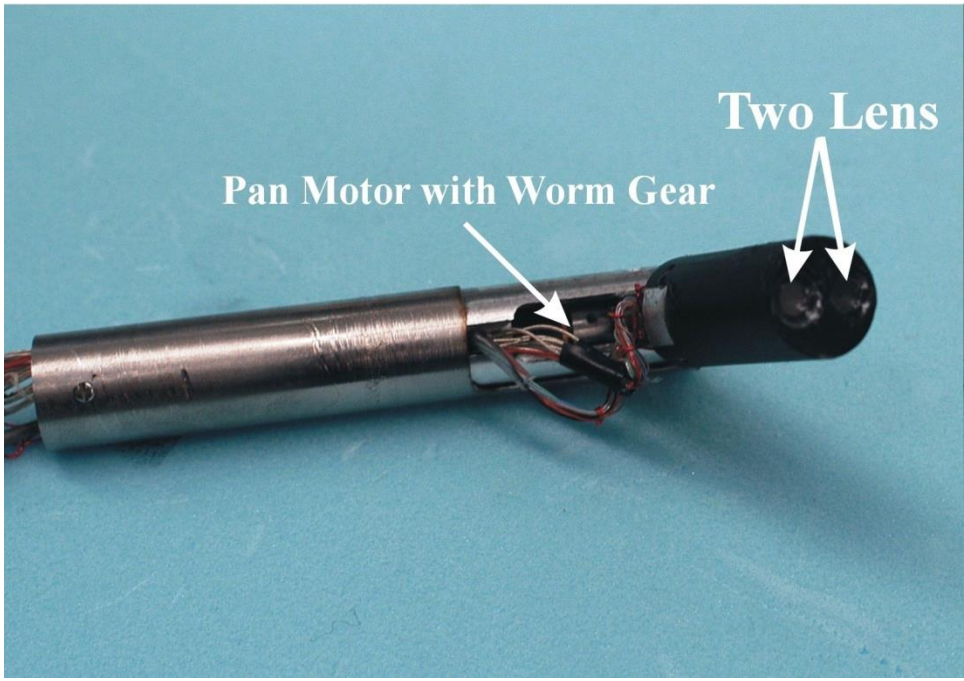
Tool Tracking



Device III: Stereo Imaging*





- A stereo imaging device with similar mechanical design.
- 15 mm in diameter and 120 mm in length.
- 6.5mm Inter-Pupillary Distance (IPD)

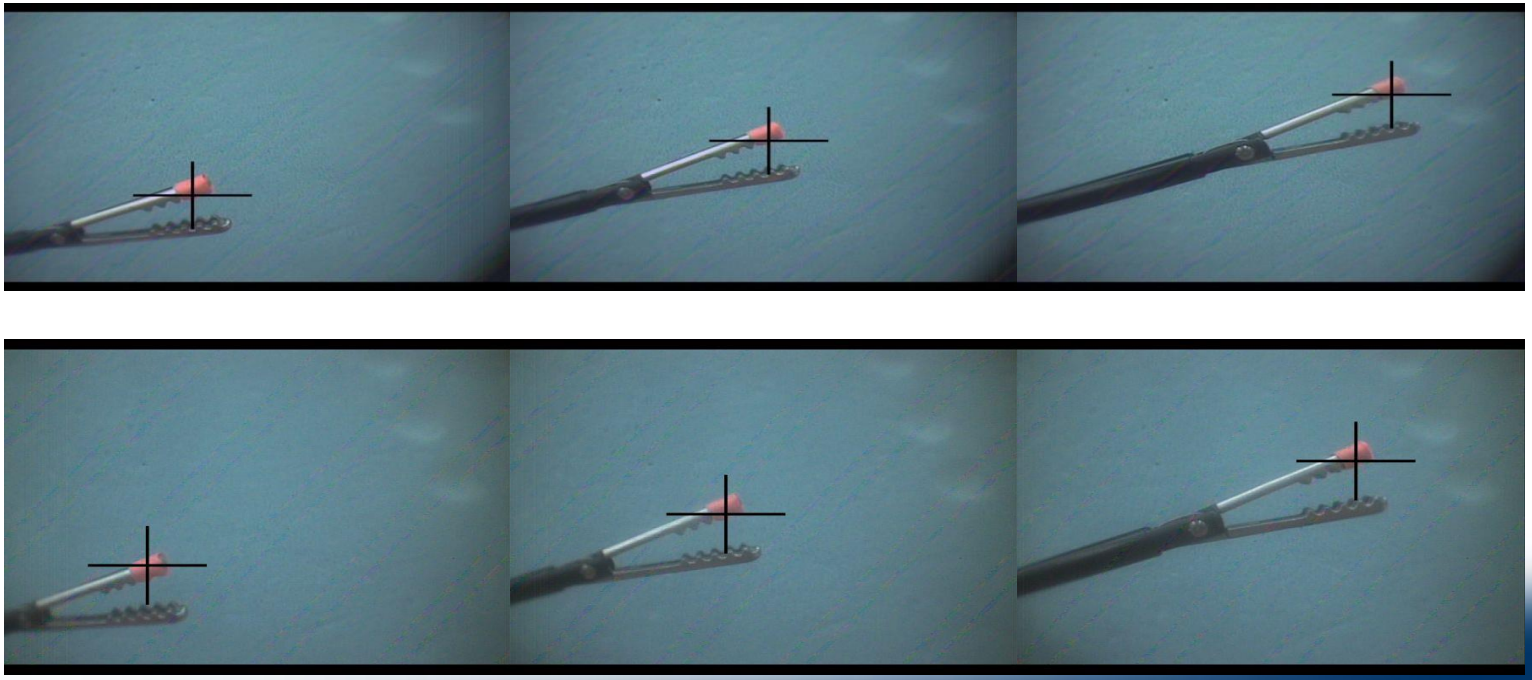
*T. Hu, P. Allen,, T. Nadkarni, N. Hogle, D. Fowler, *Insertable Stereoscopic 3D Surgical Imaging Device*, IEEE BIOROB 2008

Visual Servoing with Stereo

- When using stereo cameras the pixel disparity E_p between stereo images is used to damp the motors

$$\text{Speed Damping} \propto (\gamma * E_p)$$

- Damping is applied to both Pan and Tilt motors
- Prevents the motors from oscillating when instrument is too close to camera



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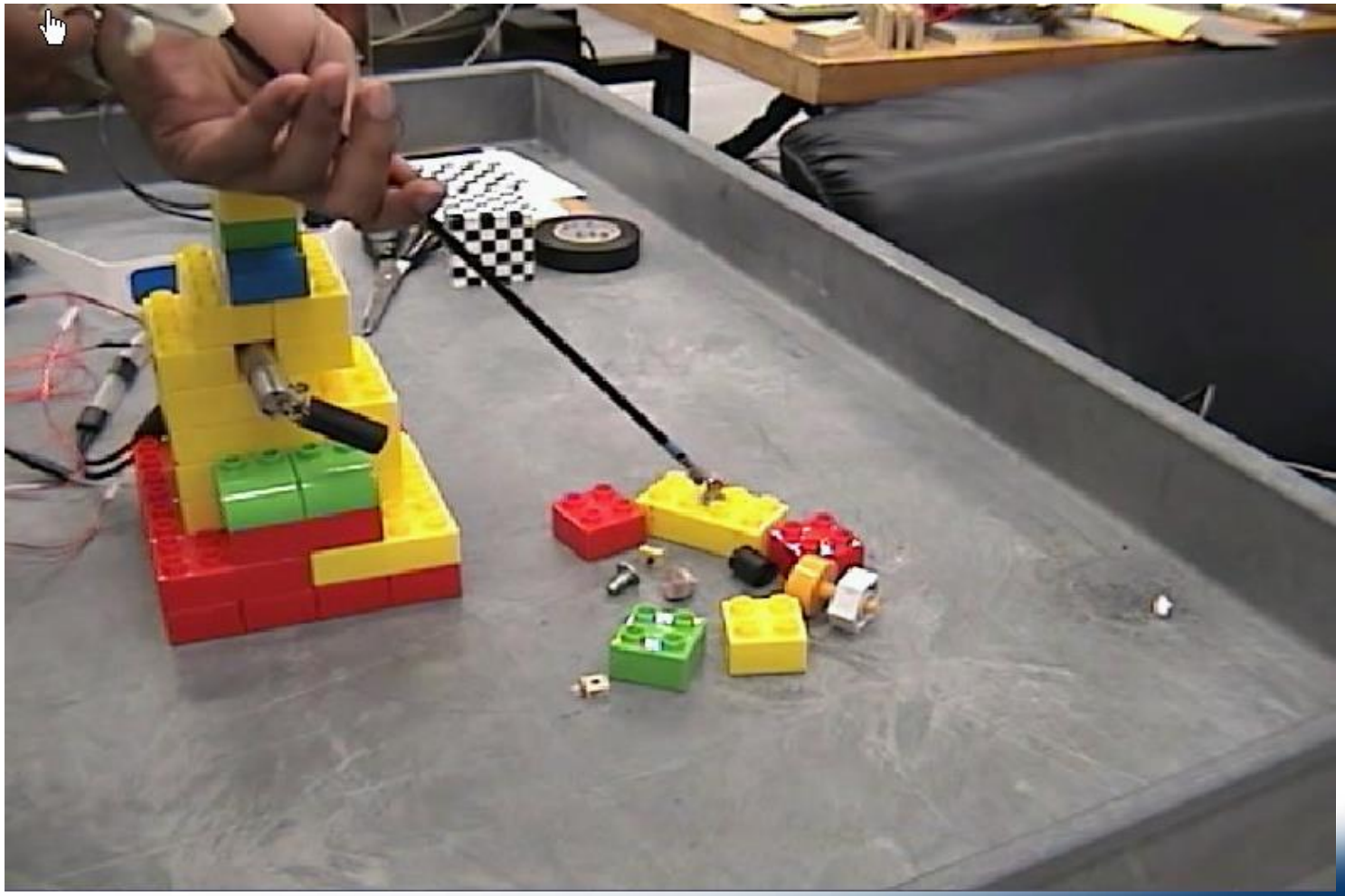
Device III: Stereo Imaging



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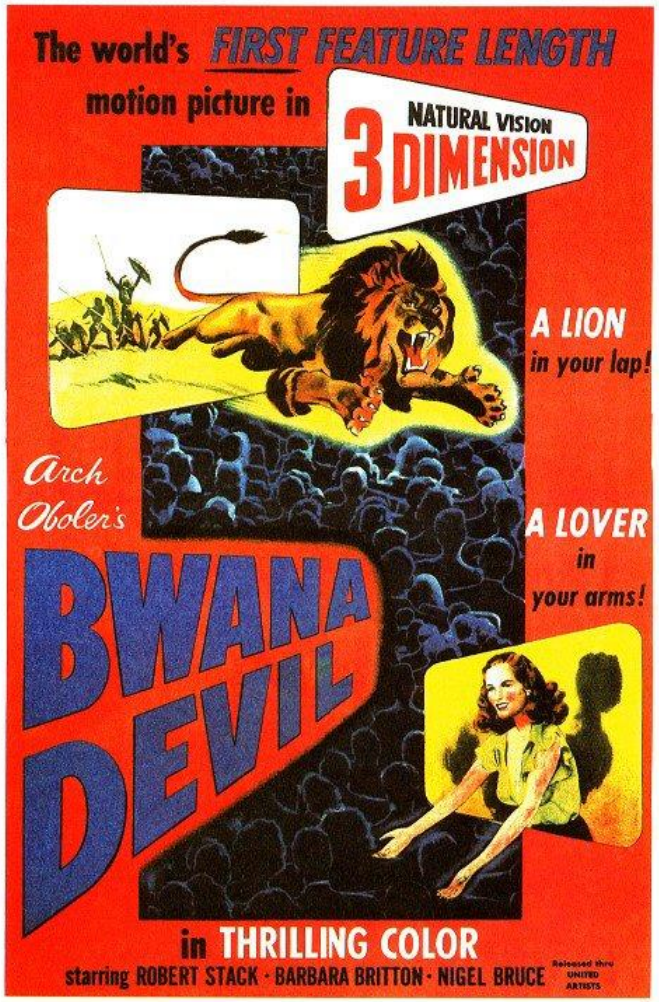
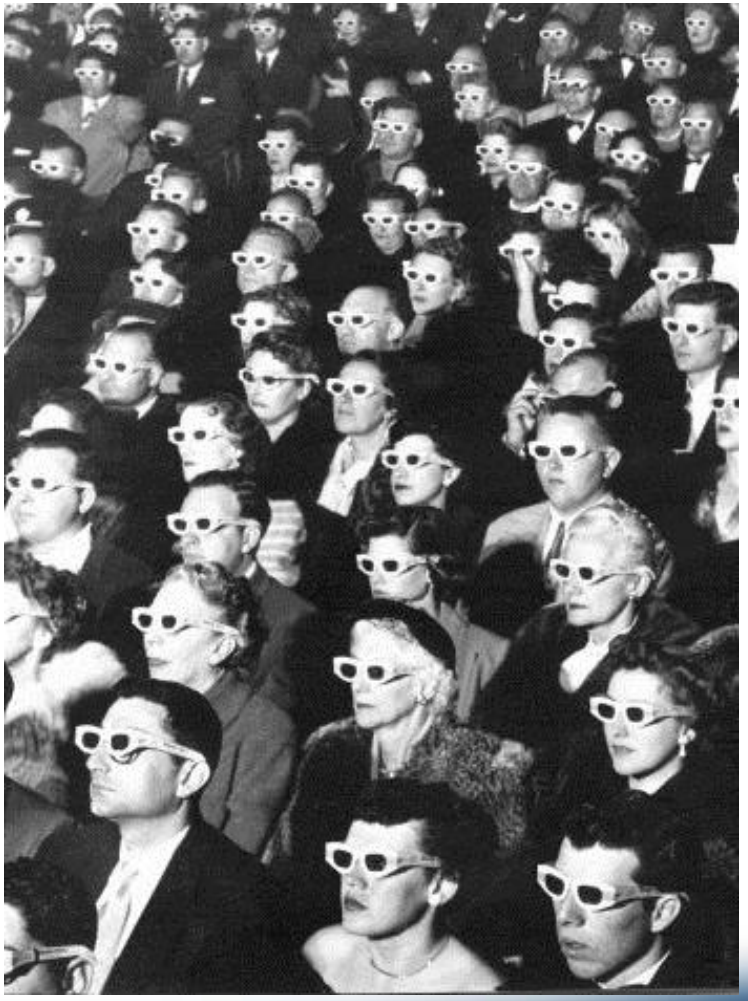
Caution: 3D viewing ahead !





Video 1

Video 2

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Stereo Imaging I

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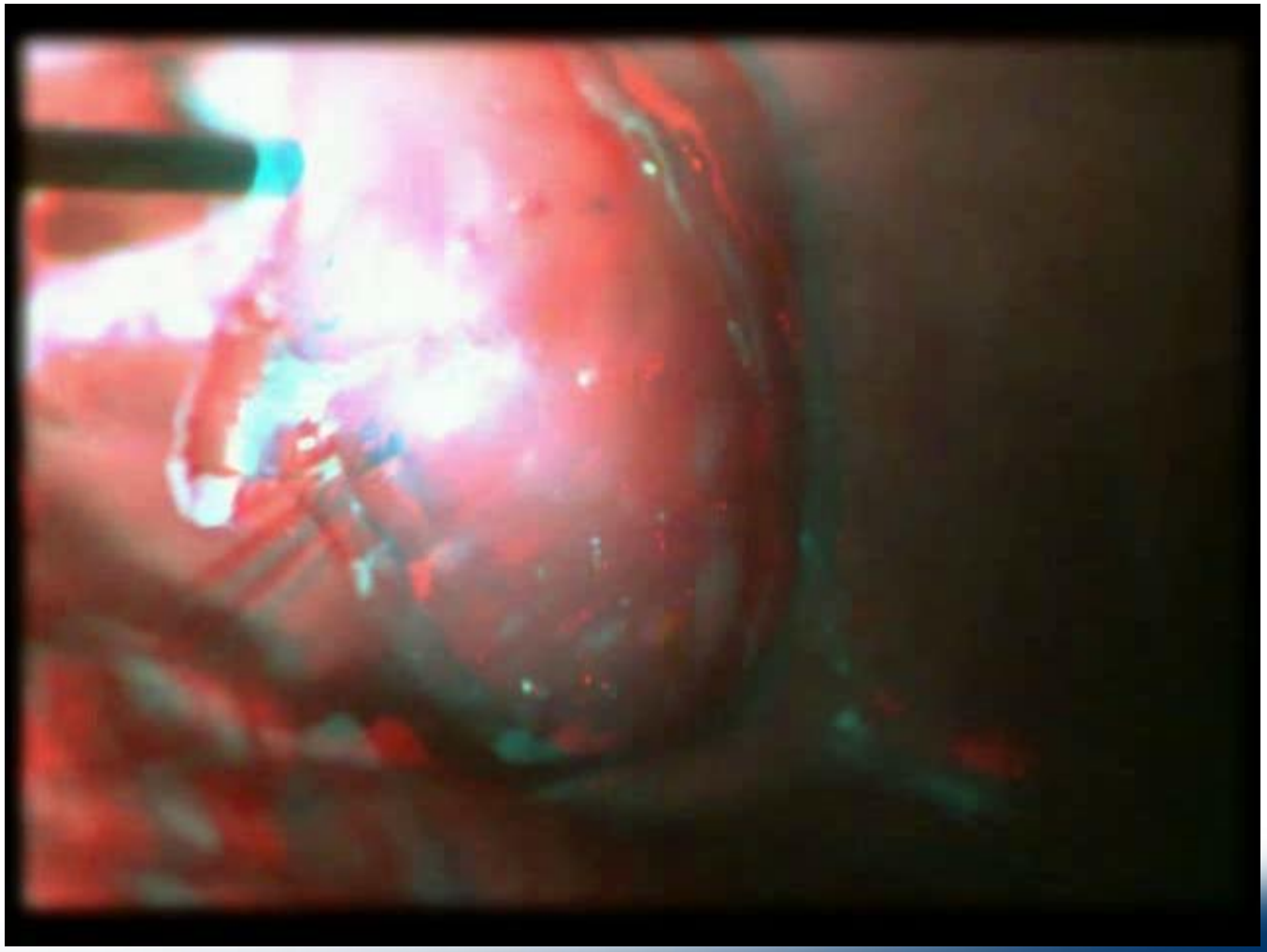
Stereo Imaging II



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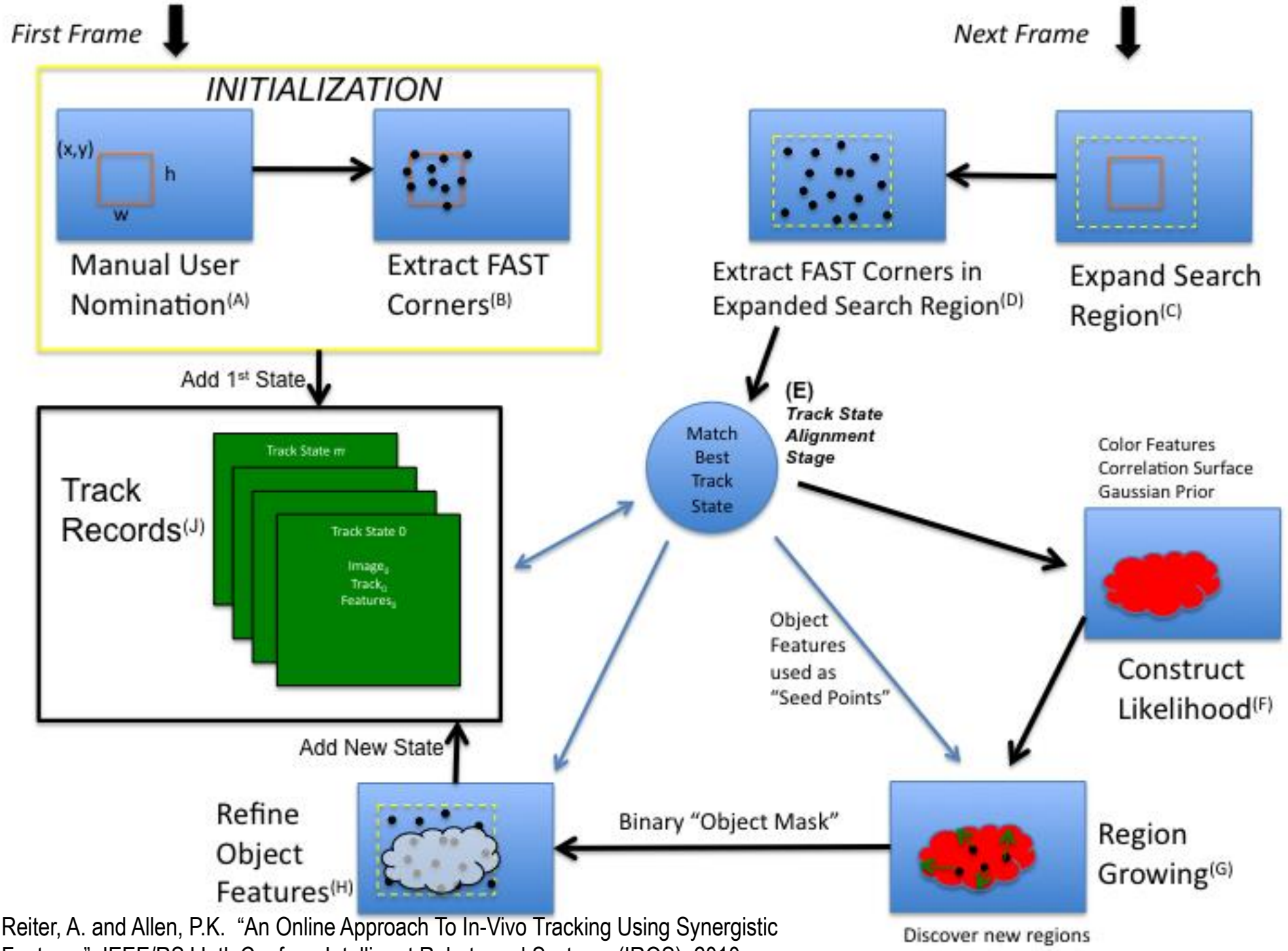
Surgical Tool Tracking

Two Methods:

Feature Flow: Multiple features tracked over time, database of history and priors for confidence

Appearance Learning: Learn tool characteristics off-line, fast recognition on-line



Reiter, A. and Allen, P.K. "An Online Approach To In-Vivo Tracking Using Synergistic Features", IEEE/RSJ Intl. Conf. on Intelligent Robots and Systems (IROS), 2010

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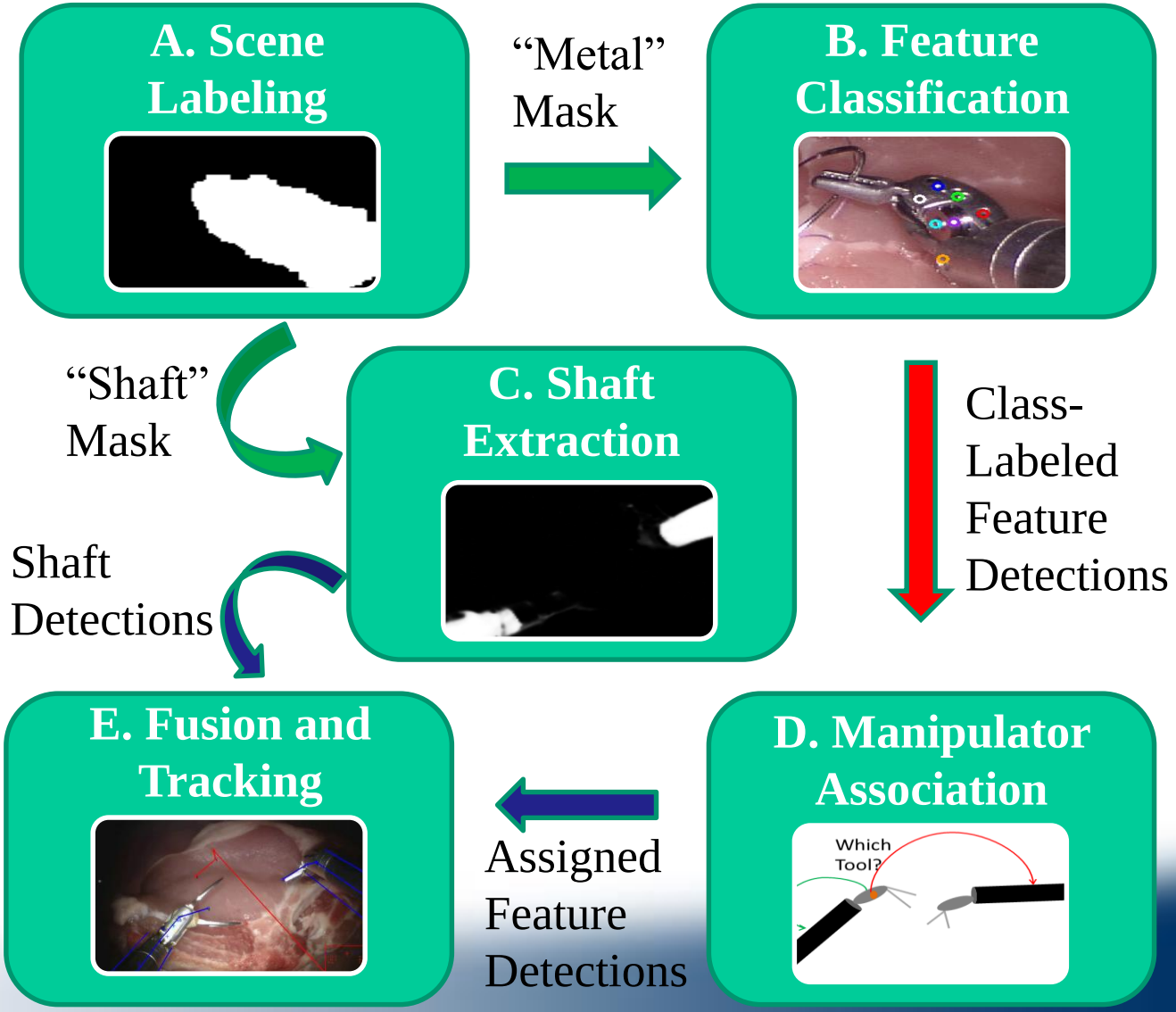
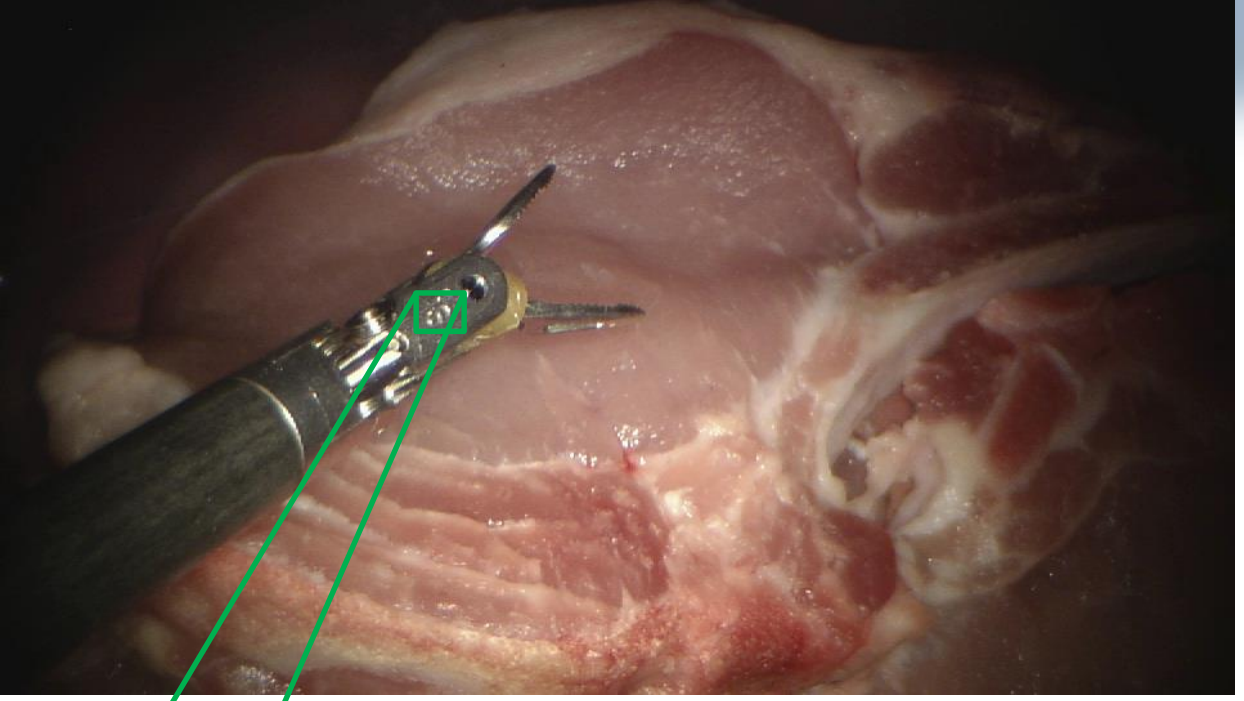
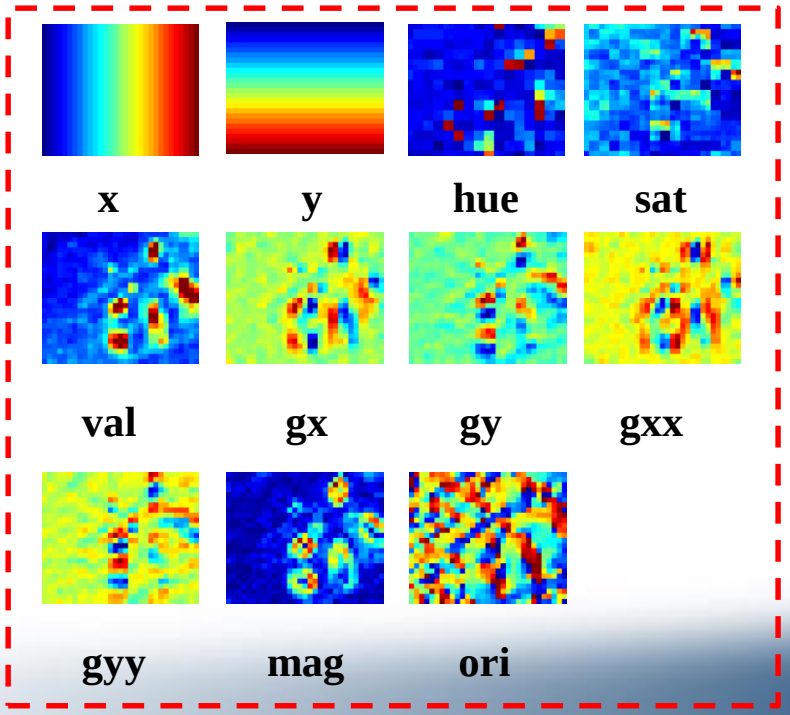
Automatic Tool Tracking: In-Vivo

Marker-less Tool Tracking Overview







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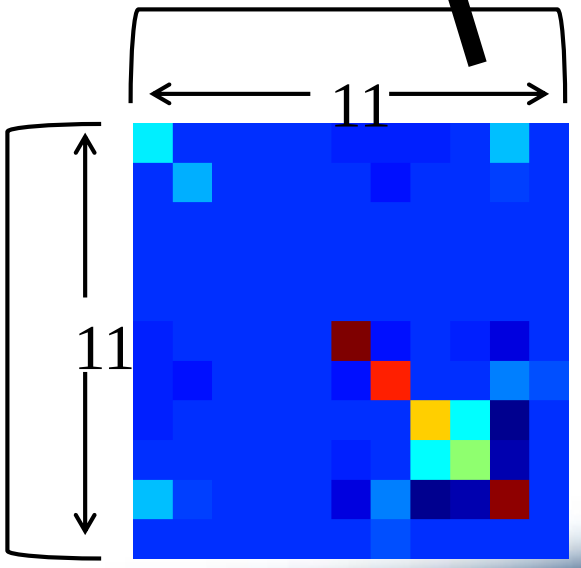
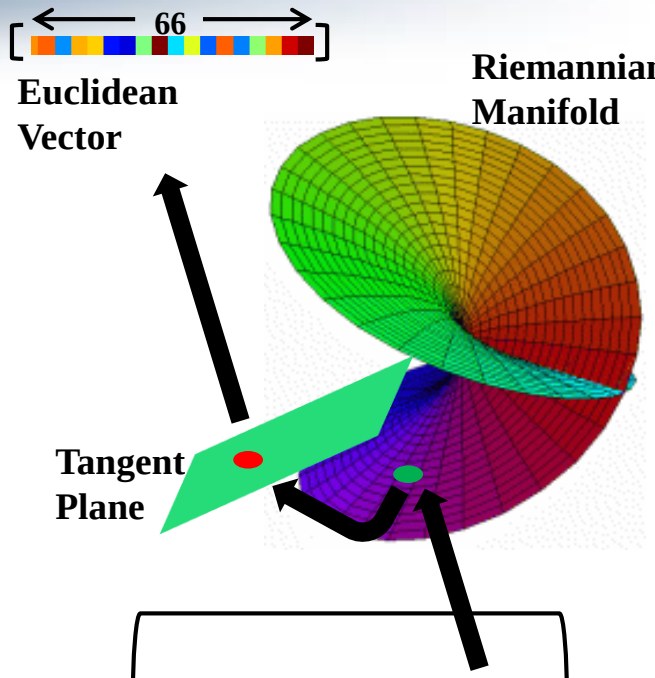




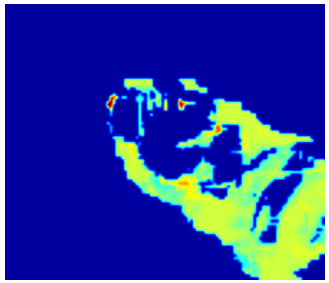
Covariance
Descriptor

Feature Detection

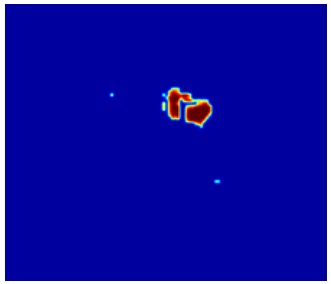
- Each classifier yields posterior probabilities at every pixel
- **Stereo depth estimation for optimal window size (very important!)**

Extrema

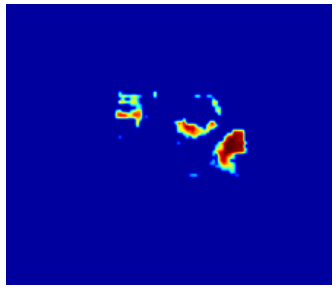
Non-maxima suppression



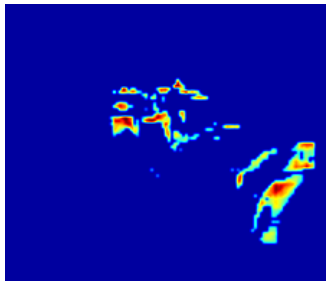
iDot



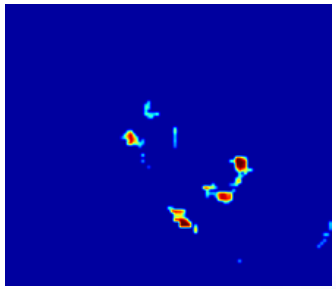
IS_Logo



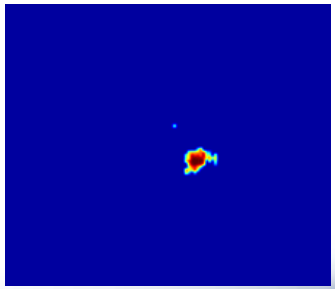
Pin1



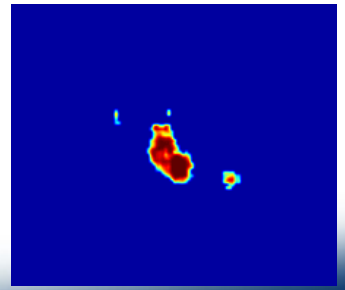
Pin3



Pin4



Wheel



Wheel_Pin

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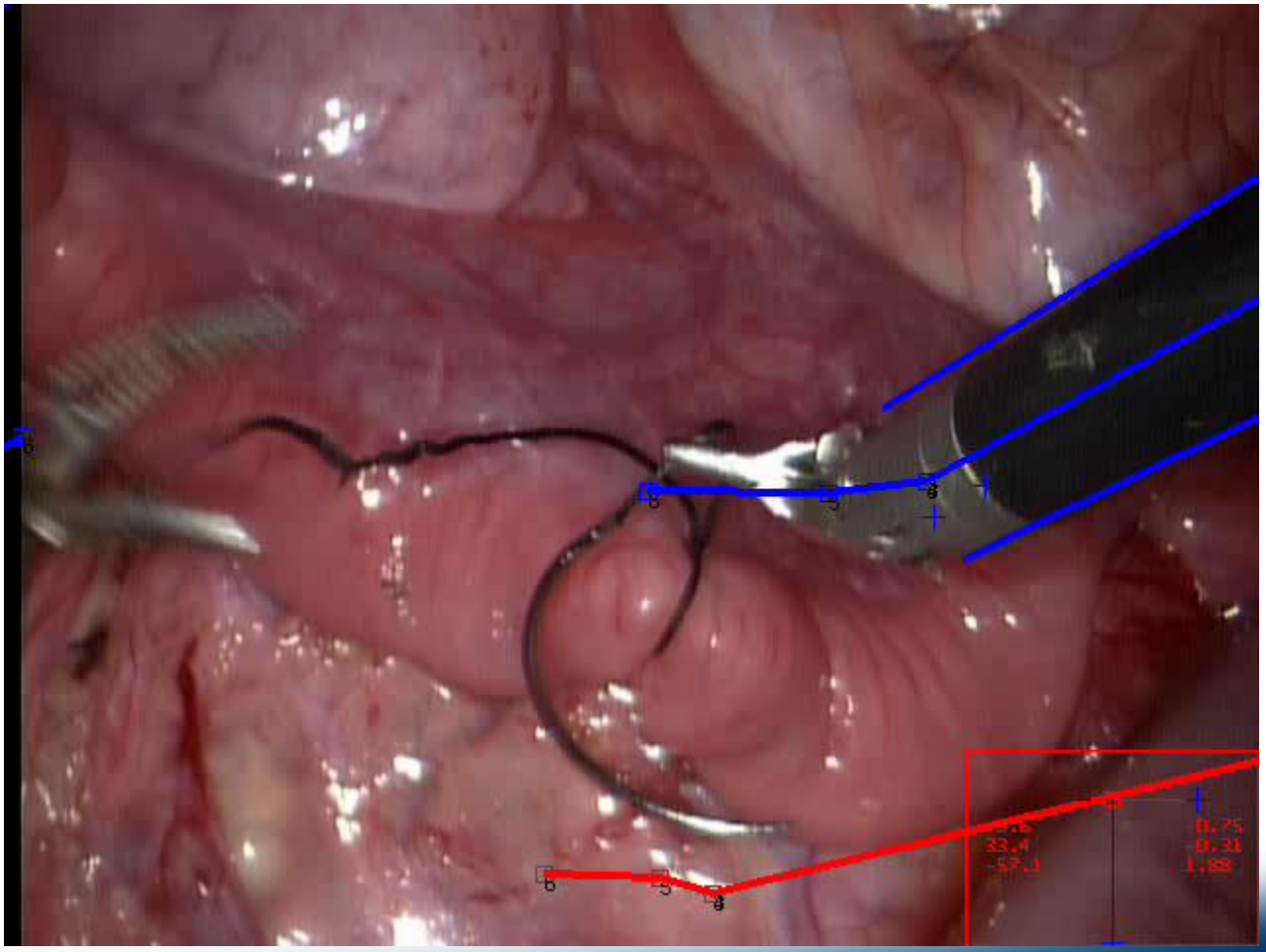
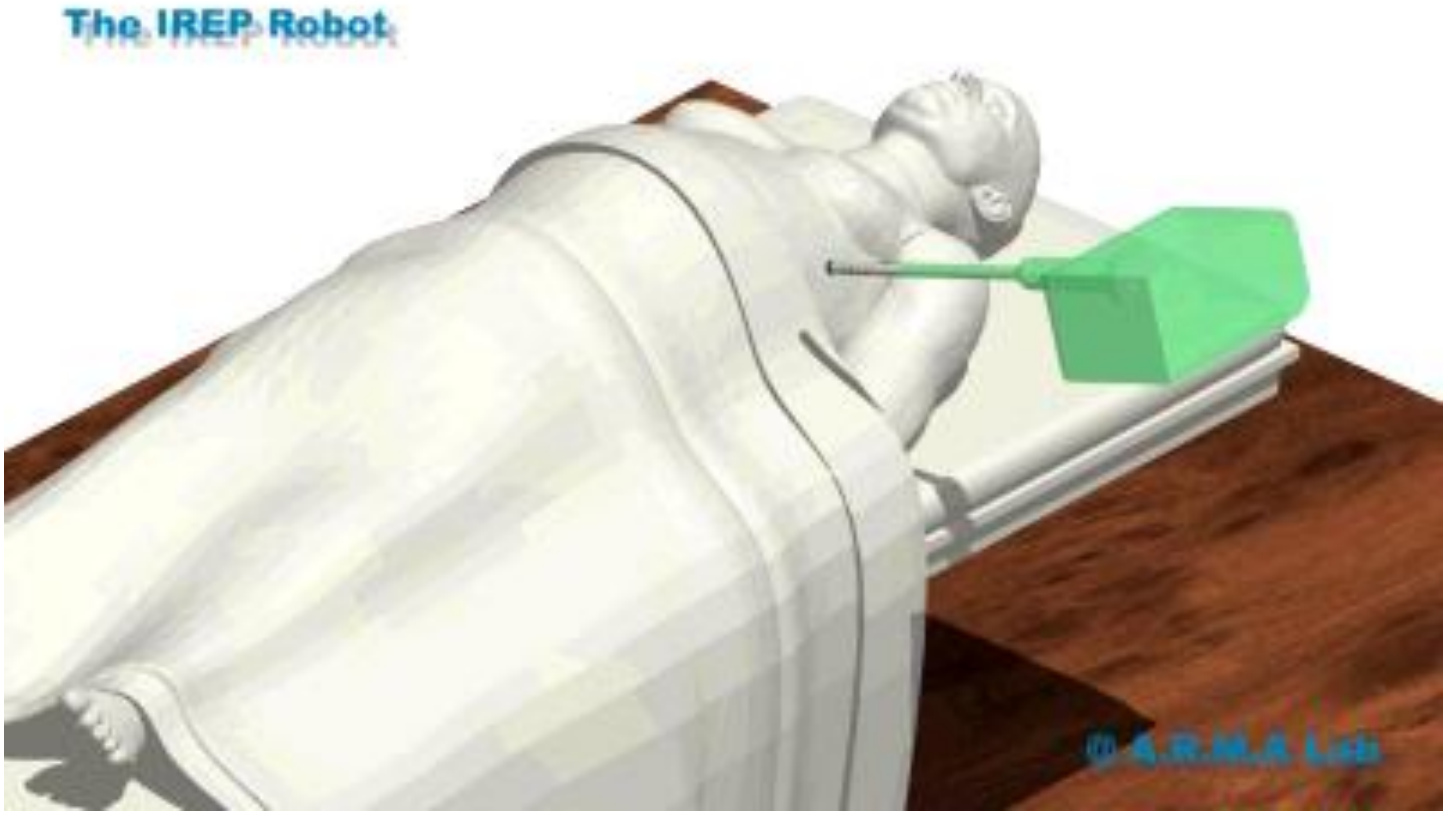
Dual Arm Tracking: daVinci



Insertable Robotic Effector Platform



K. Xu, R. Goldman, J. Ding, P. Allen, D. Fowler and N. Simaan, System Design of an Insertable Robotic Effector Platform for Single Port Access (SPA) Surgery, IROS 2009

Vision for In-Vivo Surgical Platforms

- IREP Platform integrates vision and tooling: Cameras, Graspers, Dissectors, Scissors, Energy sources
- Vision needed for:
  - Instrument tracking
  - Kinematic control
  - 3D measurement/reconstruction
- Vision system is key part of HCI
- Surgeon is focused on the task, not controlling the camera images

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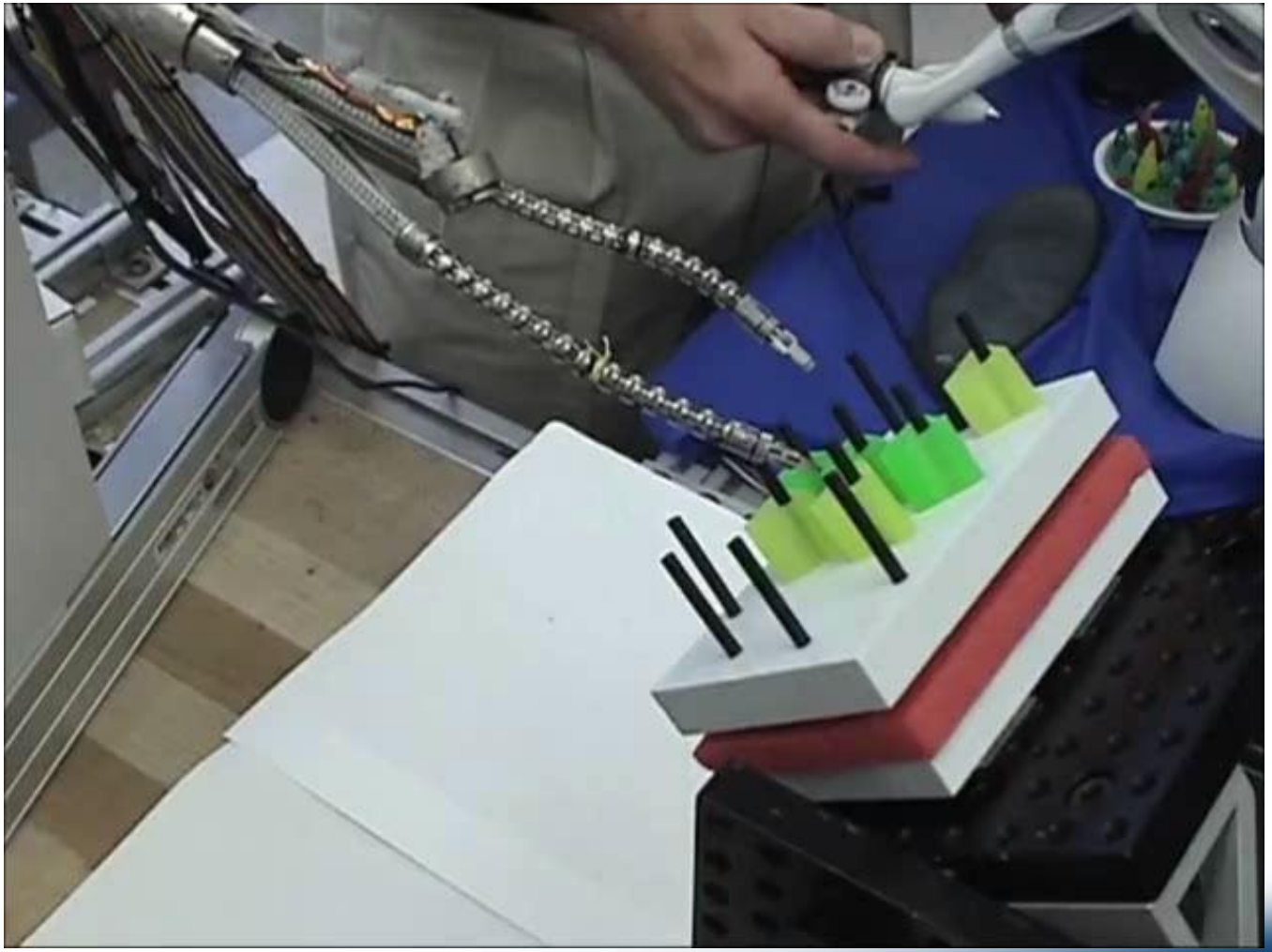
IREP Prototype



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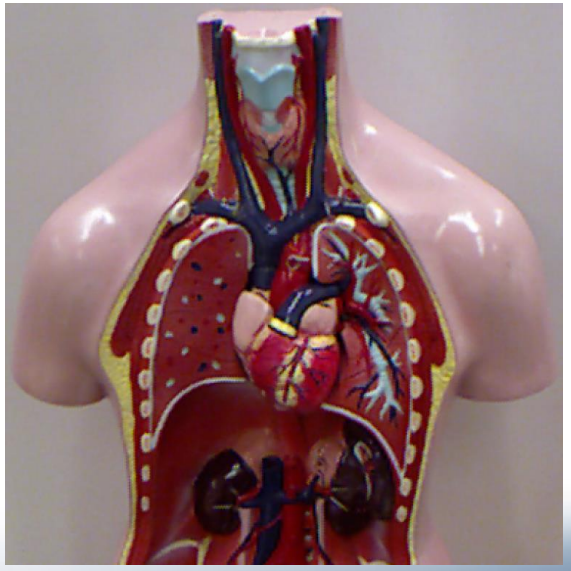
Titan Medical Device

Surgical Structured Light

- **Technology:** novel 3D imaging system for endoscopic surgery
- **Function:** Displays real-time 3D information about the surgical site – creates viewable real-time 3D model

A Single Image:

What we're used to



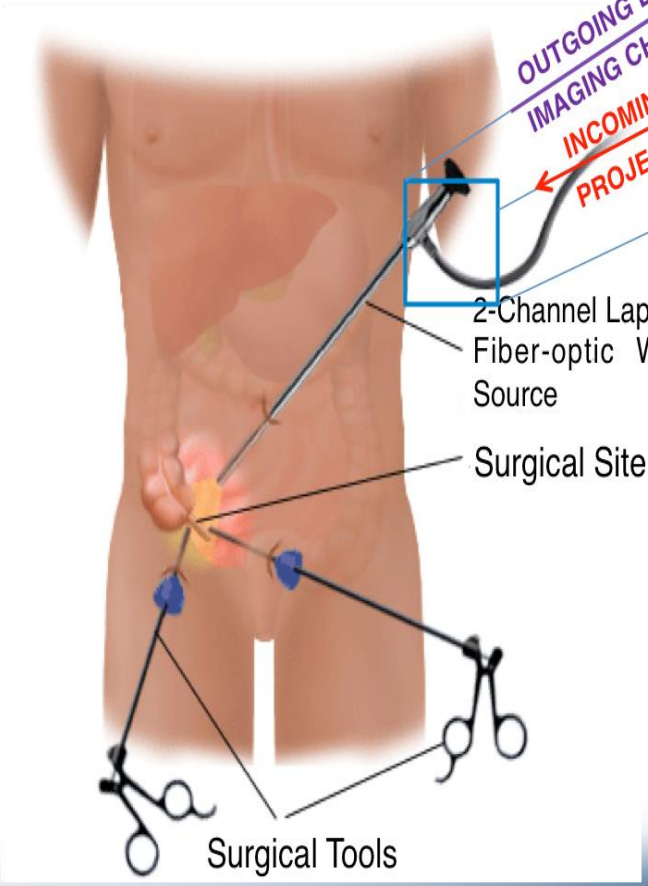
Fully-rotating 3D display:

What SSL can provide

Columbia Robotics

Surgical Structured Light (SSL)

Extending existing laparoscopic technology towards photorealistic real-time 3D imaging *in-vivo.*



DICHROIC BEAM SPLITTER

White Light Camera
- main imaging source for surgeon

Pattern Camera
- used to image projected pattern for 3D reconstruction

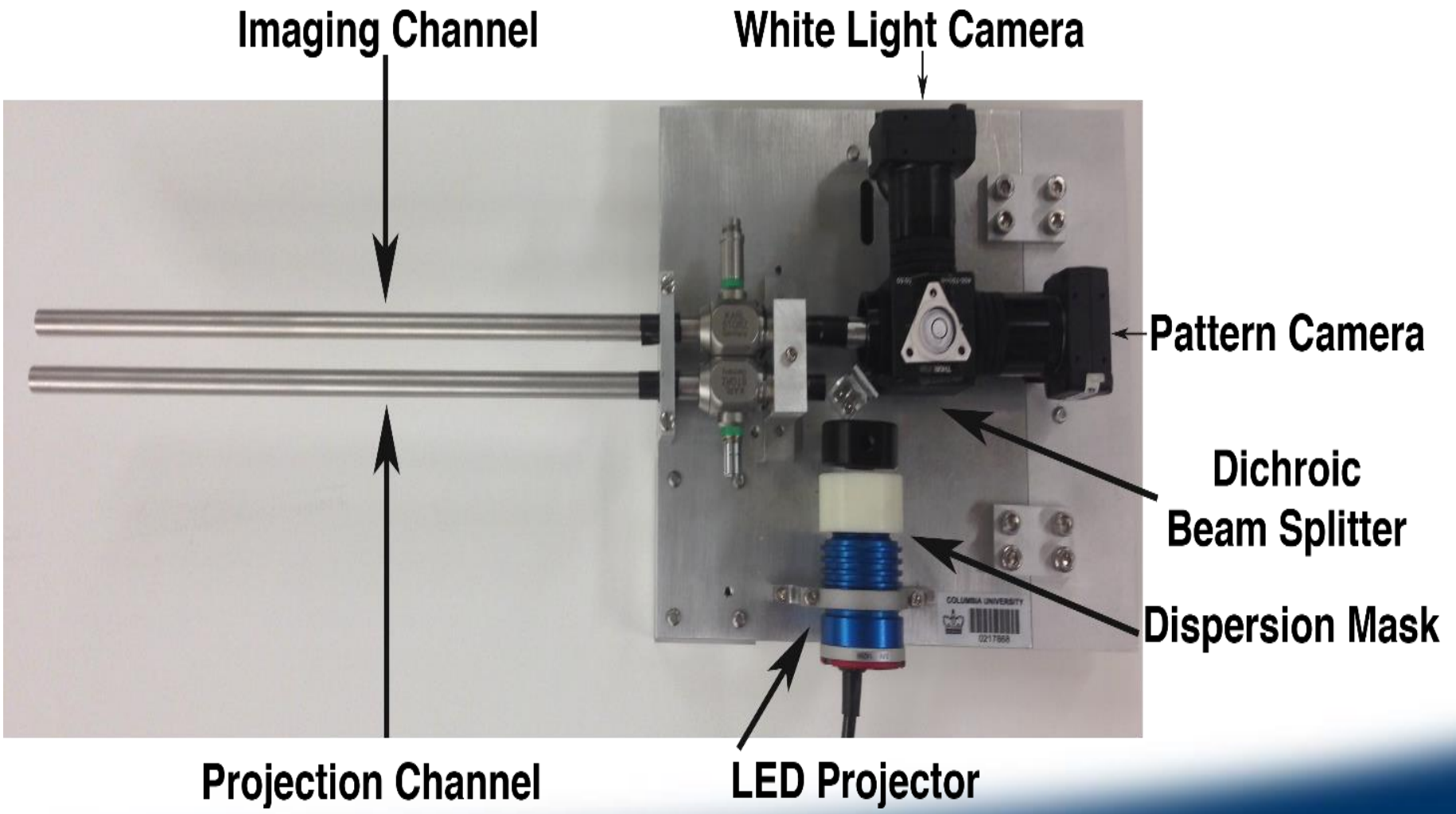
Projection Pattern

Dispersion Mask

Small-Band LED Light Source

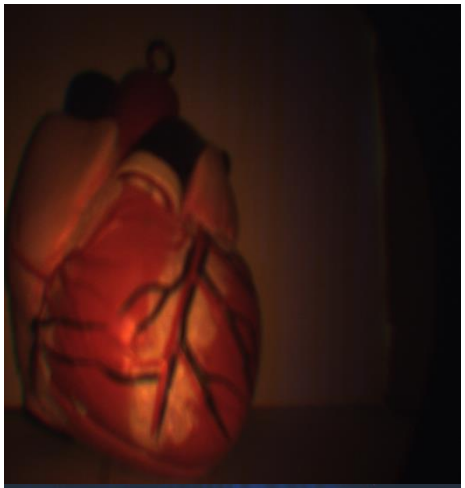
Columbia Robotics

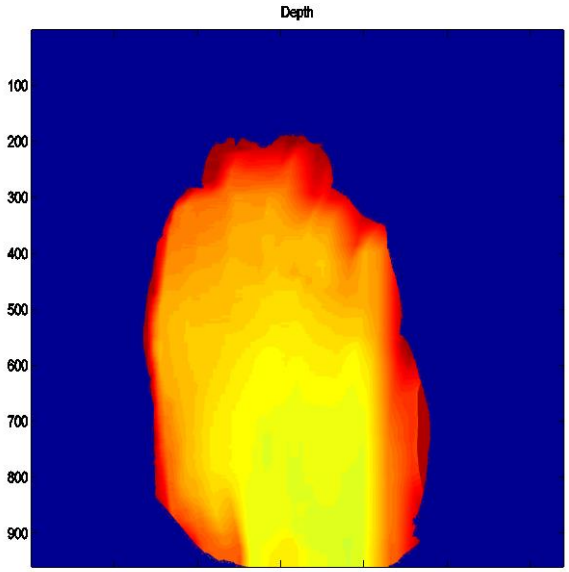
SSL Hardware

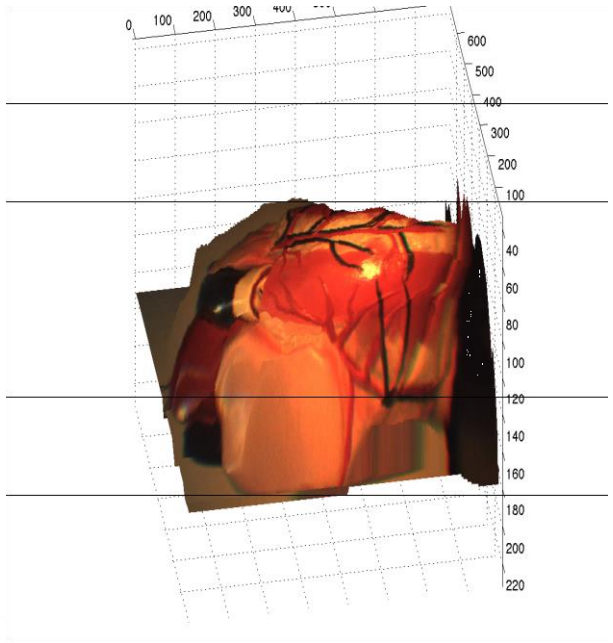


Columbia Robotics

SSL | Vision Overview







① Get Color & Blue Image

② Calculate Depth

③ Reconstruct 3D M

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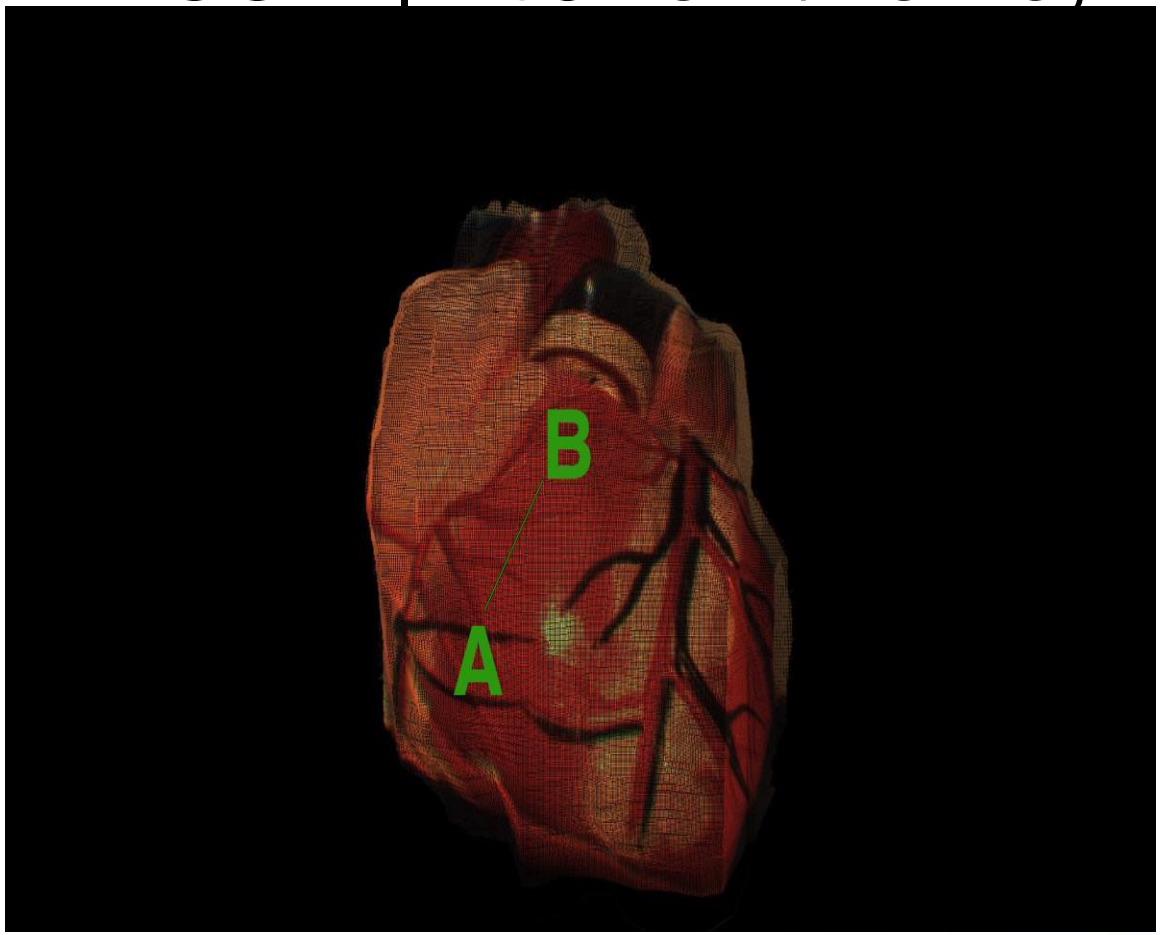
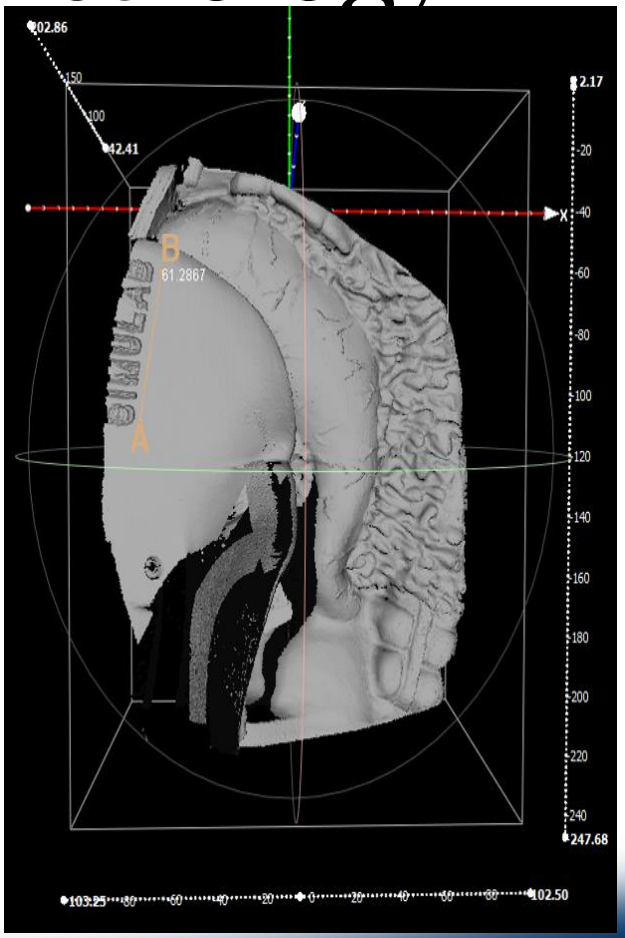
SSL | Novel Views, Metrology





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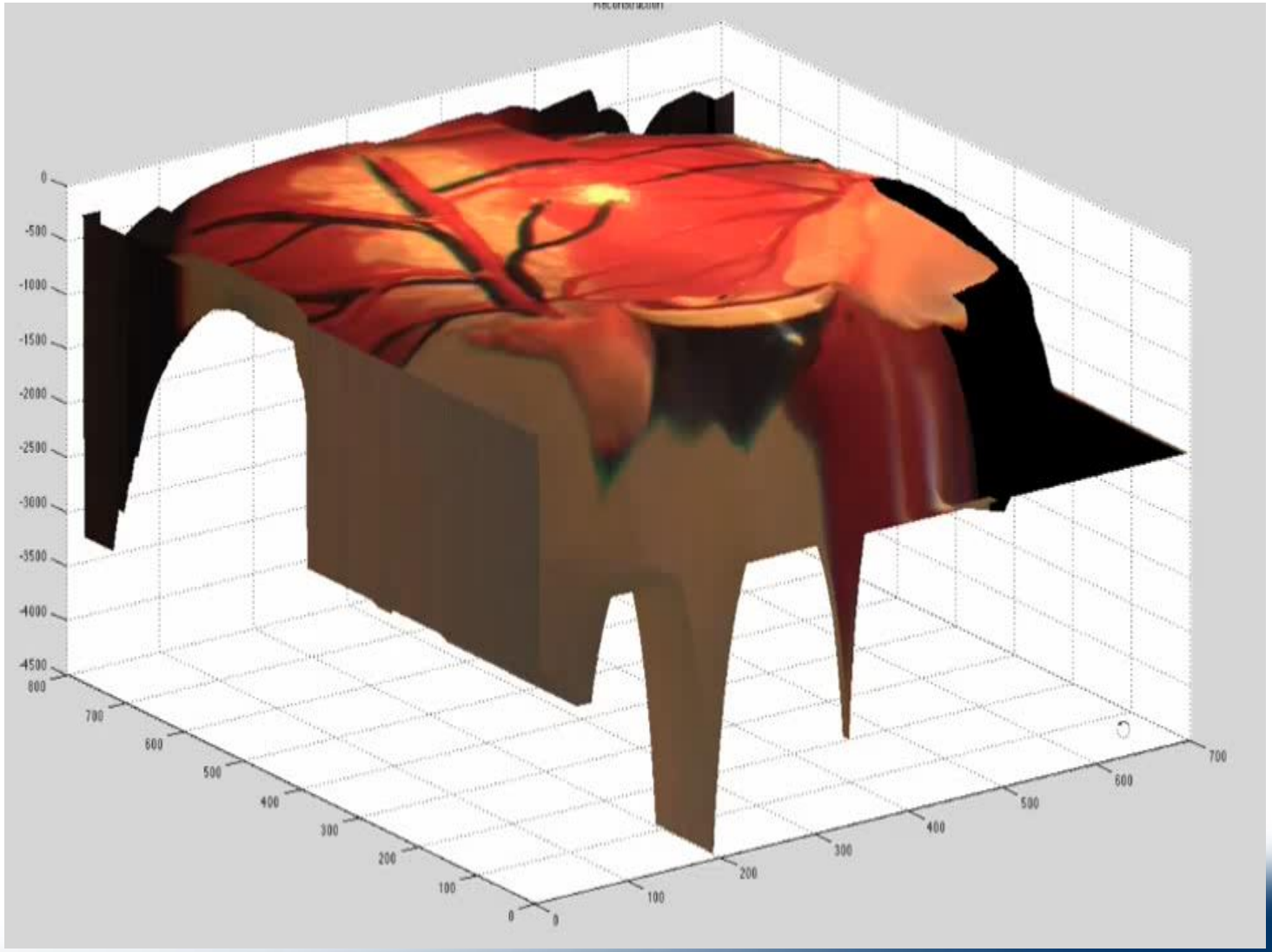
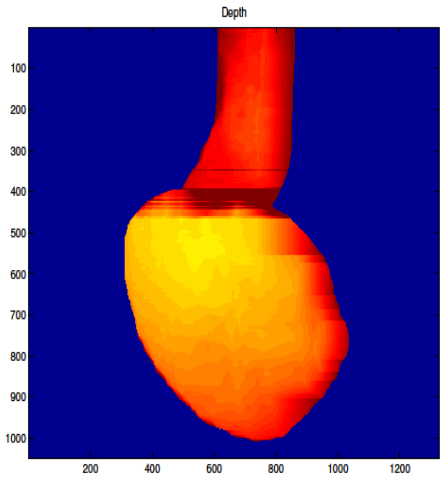
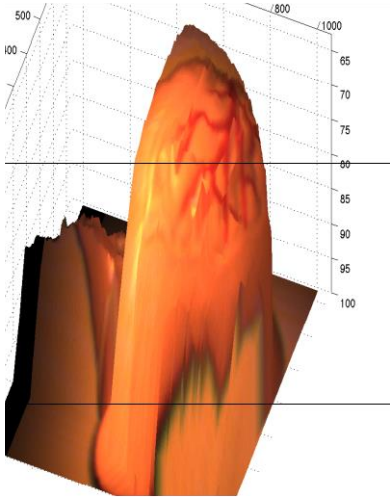
Video



Columbia Robotics

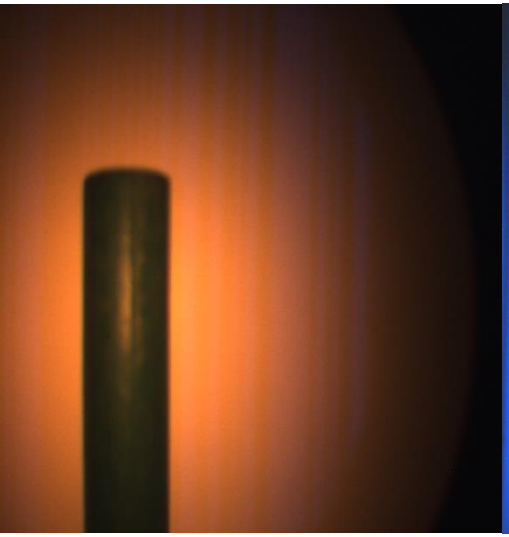
SSL |Results

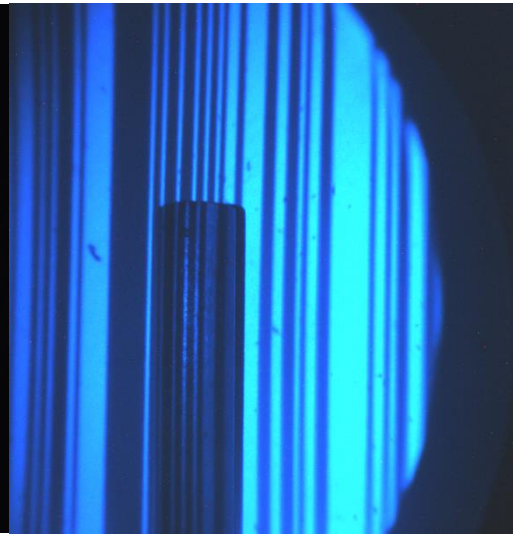


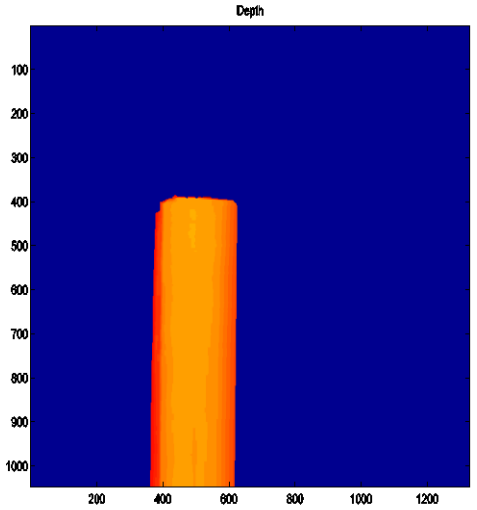


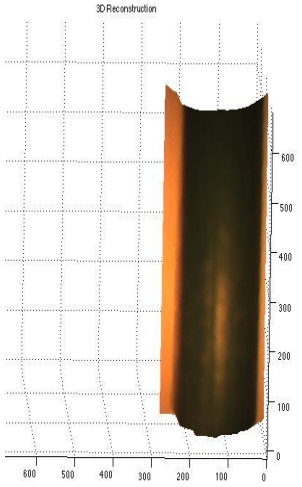
Plastic Brain

SSL |Results









Cylinder

	Distance from laparoscope	**Height**	**Diameter**
Actual	82.5 mm	62.22 mm	17.5 mm
SSL	82.5mm ± 0.6 mm	~63.8 mm	17.7 mm

What do Surgeon's want in a Robot?

Performance & Ease of Use

- Performance
  - 6+ degrees of freedom
  - Imaging integration
  - Open interfaces
  - Integration: robot-instrument
- Usability
  - Easy to setup (pre-op)
  - Intuitive interface
  - Flexible cockpit/console
  - Single/multiple console
  - Imaging integration in console

Design & Training

- Esthetics
  - Versatile/integrated design
- Cost
  - Multi-procedure adaptation
  - Low cost of operation
  - Open-ended design for upgrade
- Training
  - Efficient training program
  - Certificate of training