Next-Generation Robotic Surgery

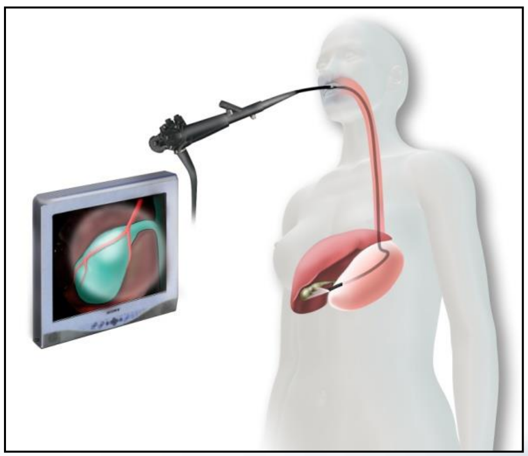
Peter K. Allen
Department of Computer Science
Columbia University

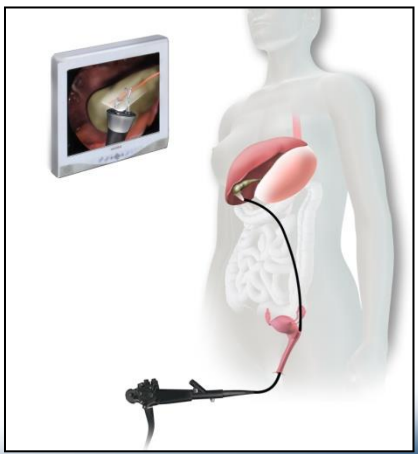
CU Robotics Medical Devices

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

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





Current Generation Robotic Surgery

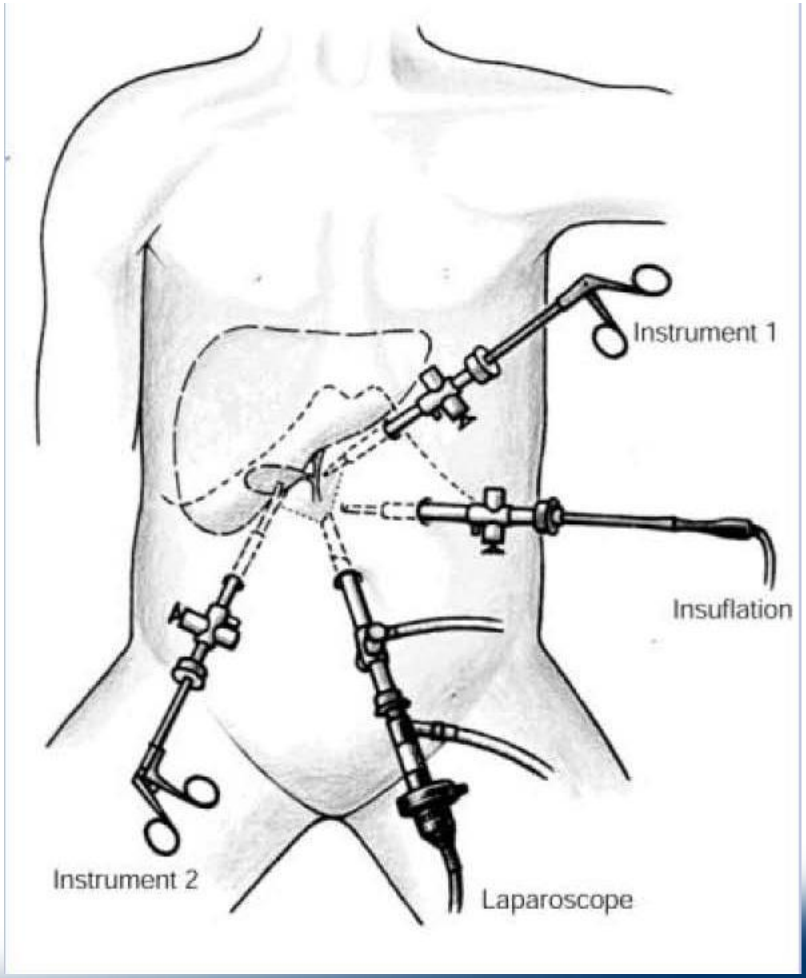
Devices such as DaVinci®
Huge leap in robotics, but:

- 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**

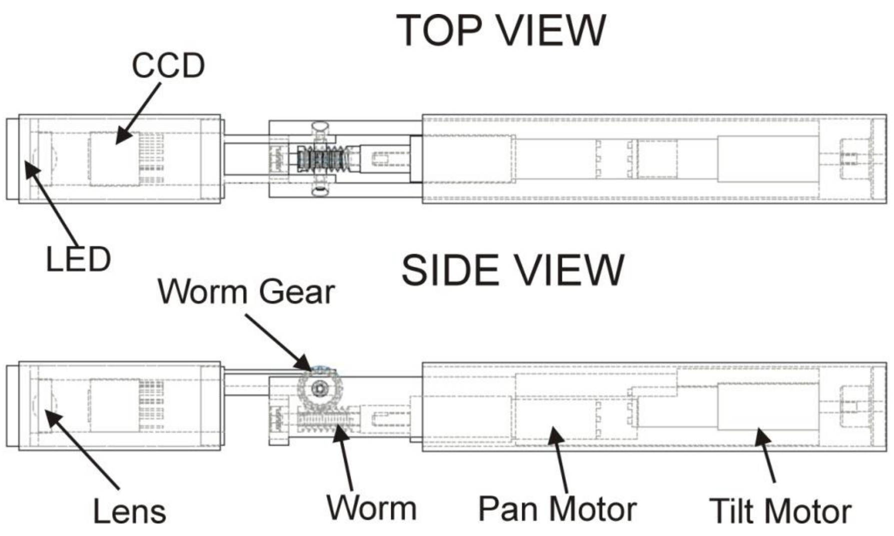
Problems with Current Imaging Devices

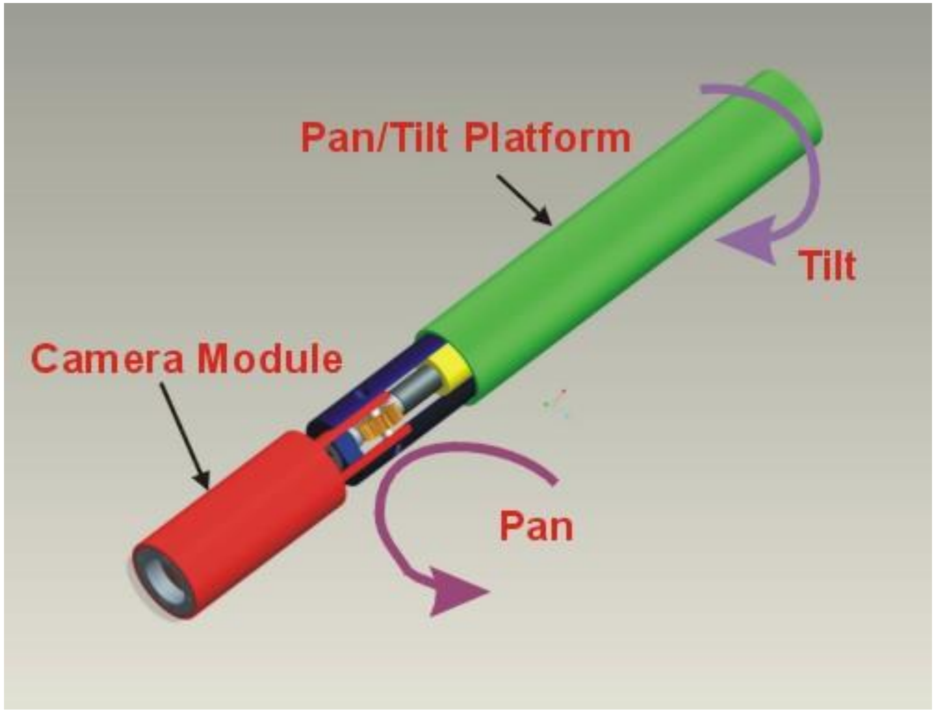
Can we improve on the traditional laparoscope?

- 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.



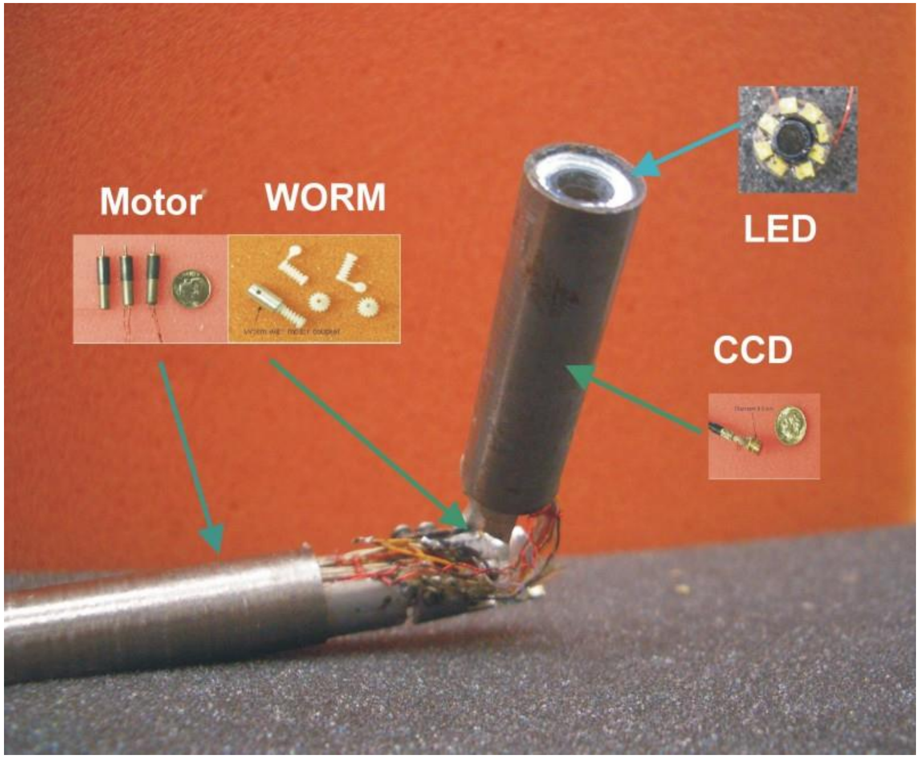
Device I: Single Camera





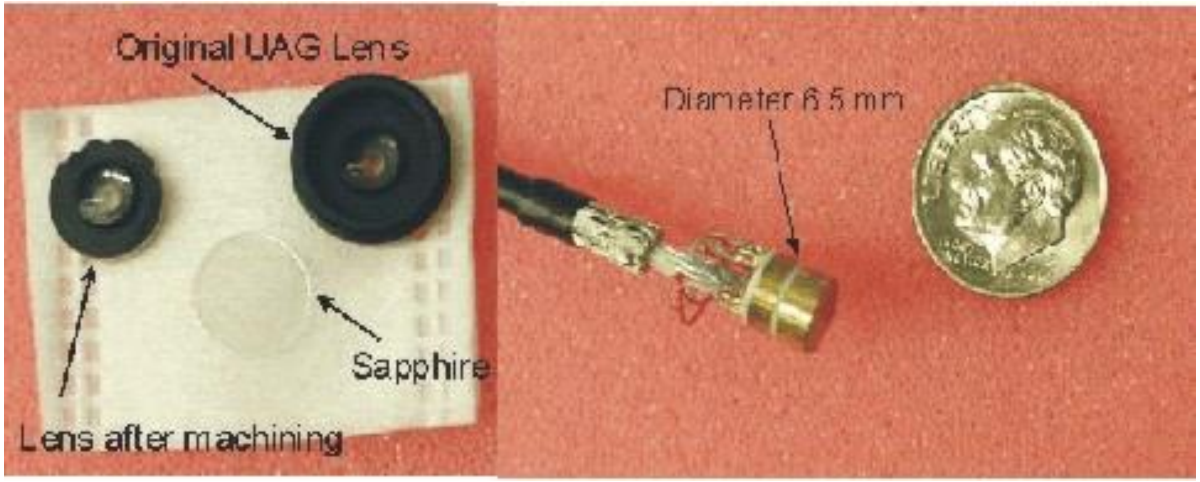
Device I: Single Camera*

- 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

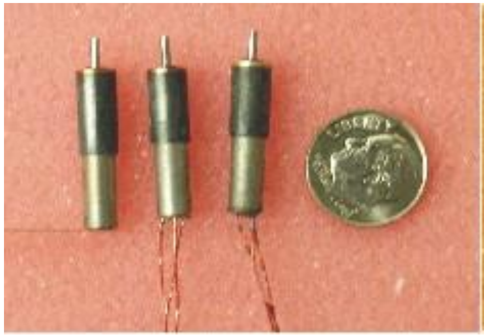
Lens and Camera Unit

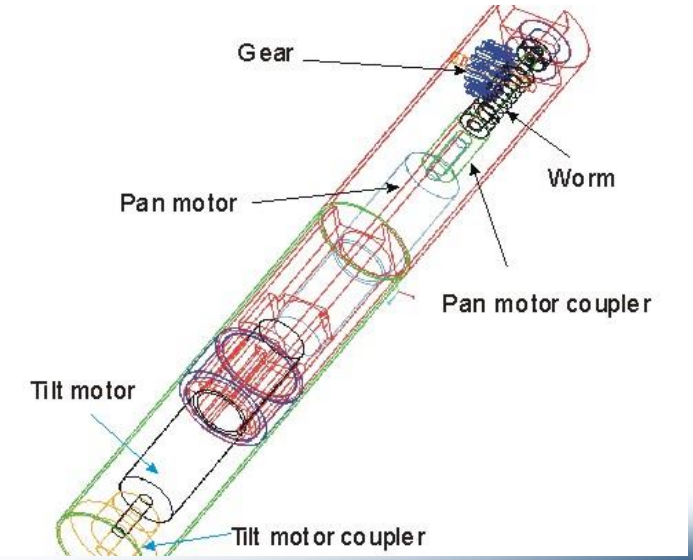


- Pin hole lens
  - Focal length 5.0 mm, F number 4.
  - Angle of view D-H-V(85.4-68.3-50.9).
- 6.5 mm CCD camera sensor.
  - 450 TV lines in horizontal resolution and 420 TV lines in vertical resolution.
- Fully sealed package to isolate body fluid and moisture.

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.

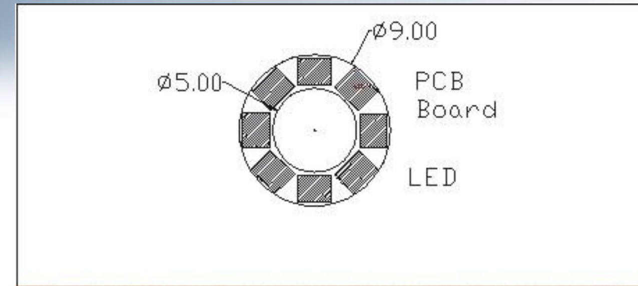


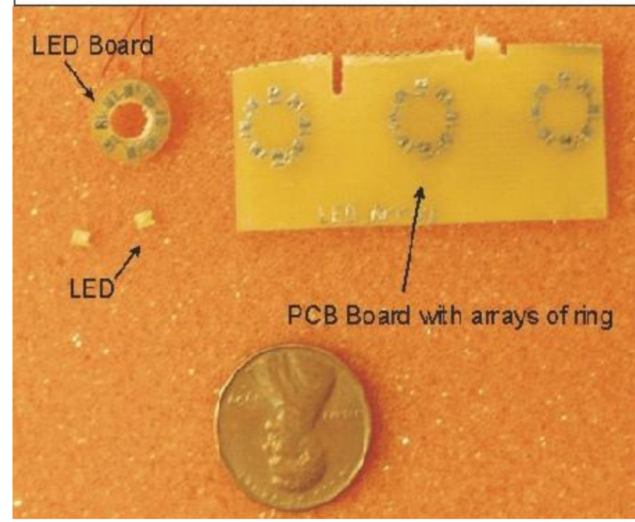


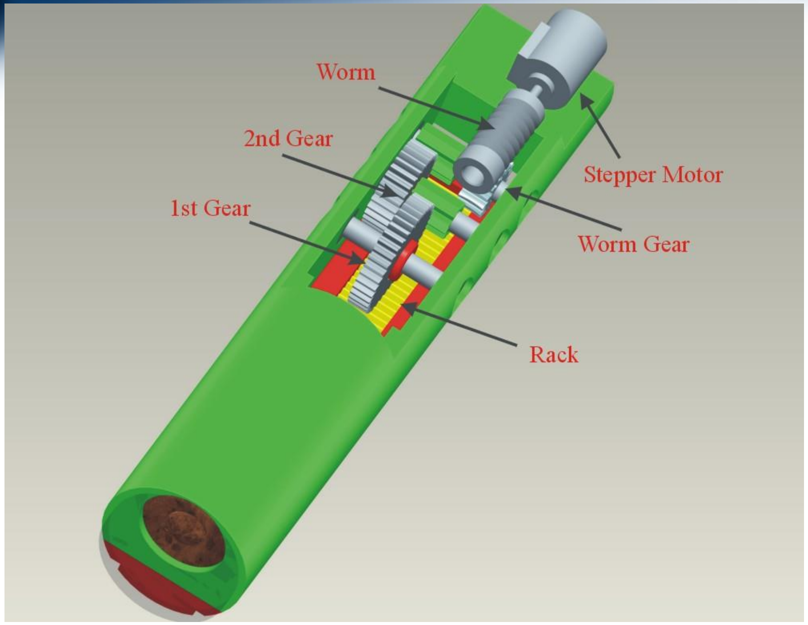
Columbia Robotics

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



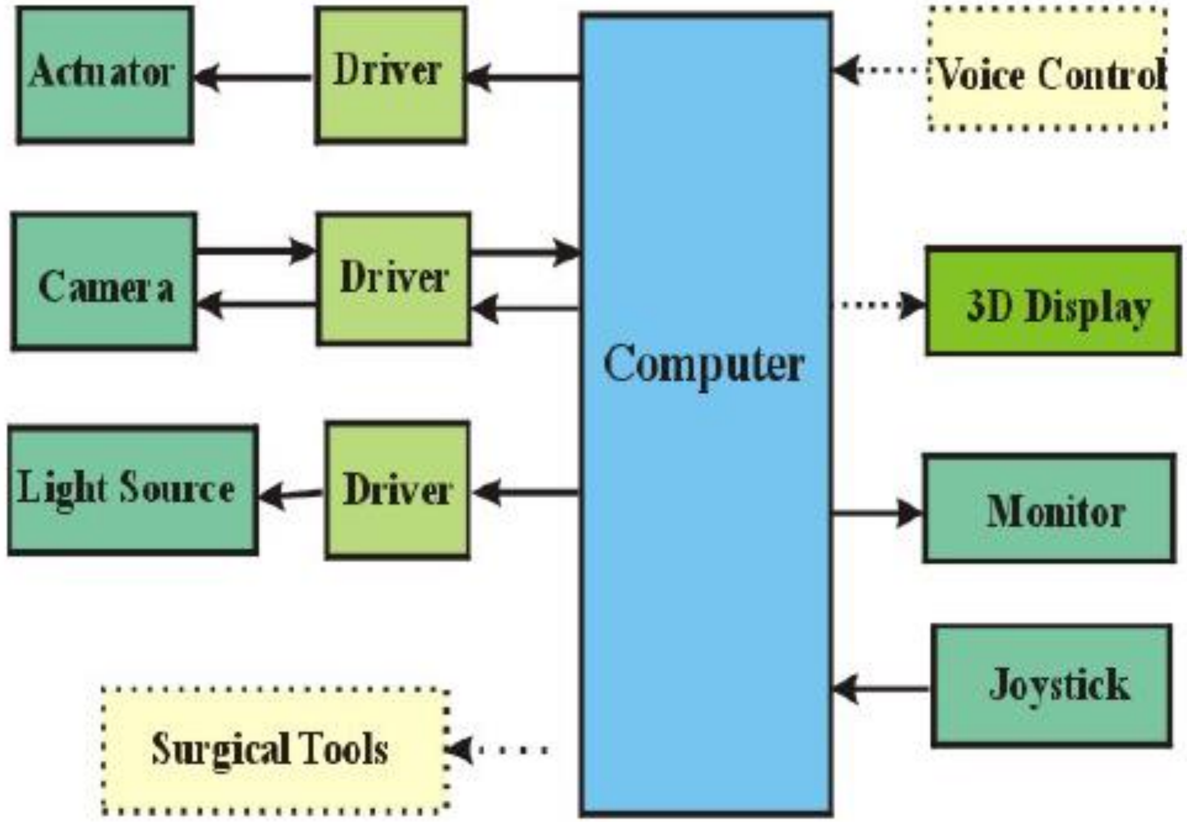




Device II: Pan, Tilt, Zoom

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

System Architecture

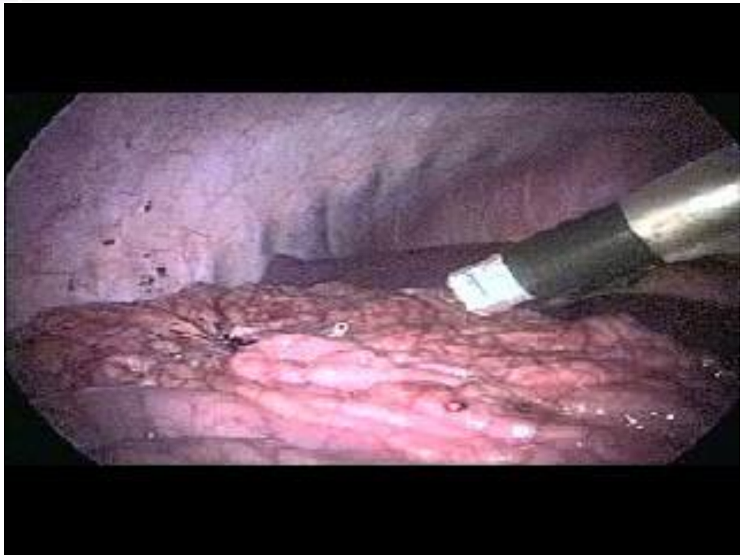


No expensive console needed, just a standard PC!

Mounting the Camera

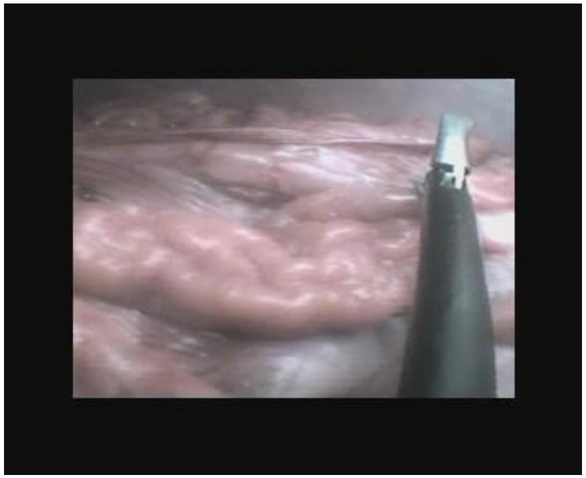
- Camera attached to insuflated abdominal wall
- Attachment methods:
  - Suturing: small stitch through abdomen
  - Magnets
  - “Fish Hook” which grabs the abdominal wall
  - Intelligent trocar for attachment

Suturing the Camera

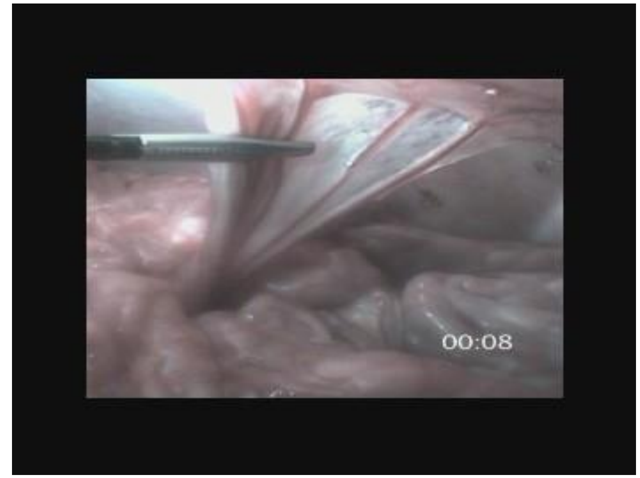


Columbia Robotics

In-Vivo Animal Experiments



Bowel Running



Appendectomy

Video

Suturing

Nephrectomy

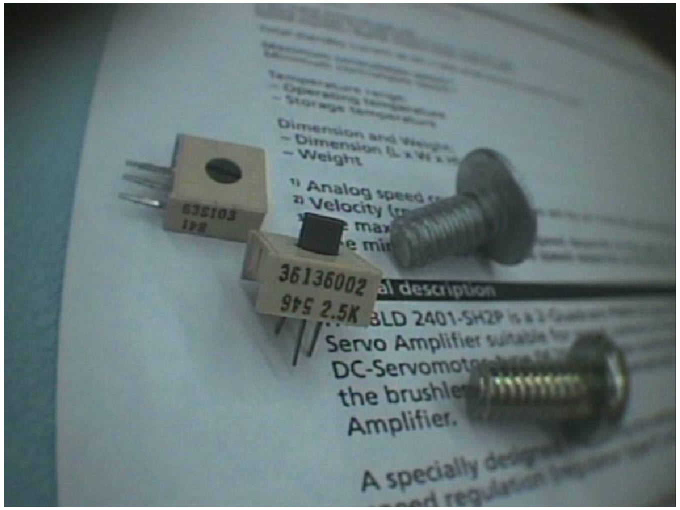
Intelligent Software

- 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

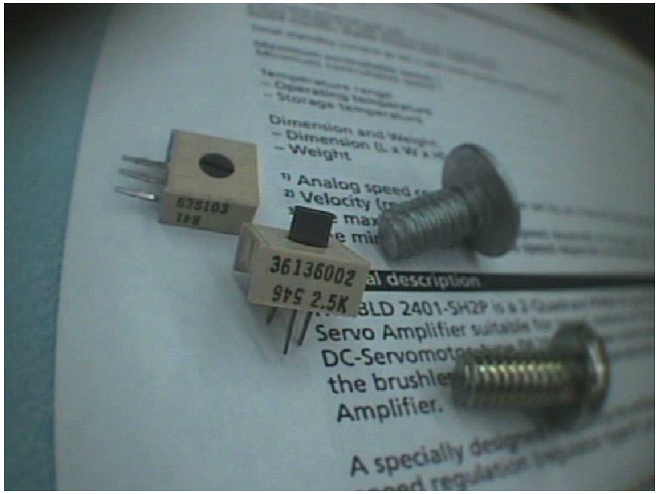
Columbia Robotics

Image Processing

Zoom :

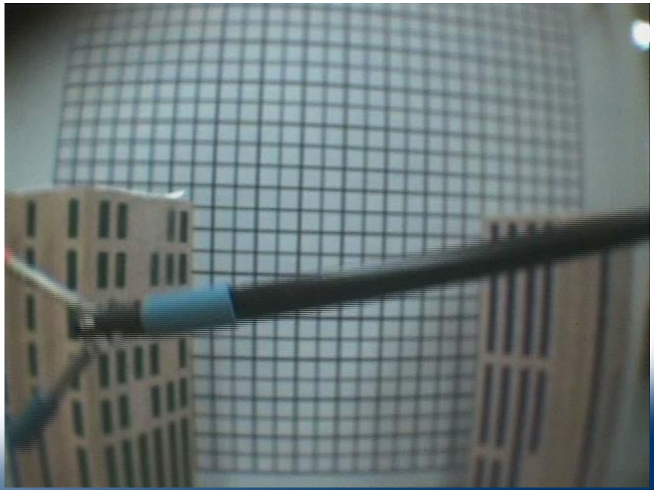


Picture in Picture :



Rotation :

Distortion Correction :



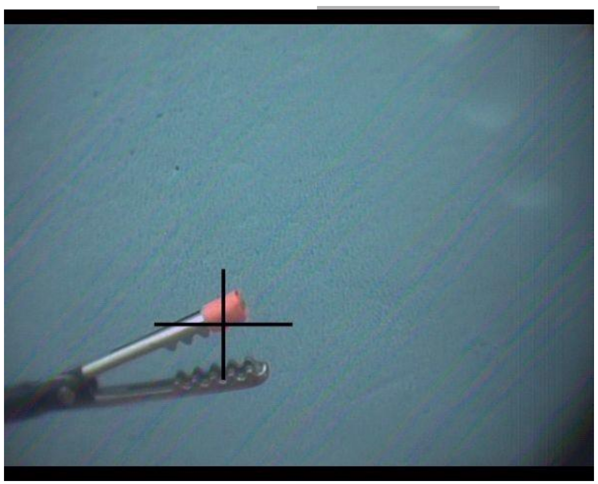
Visual Servoing

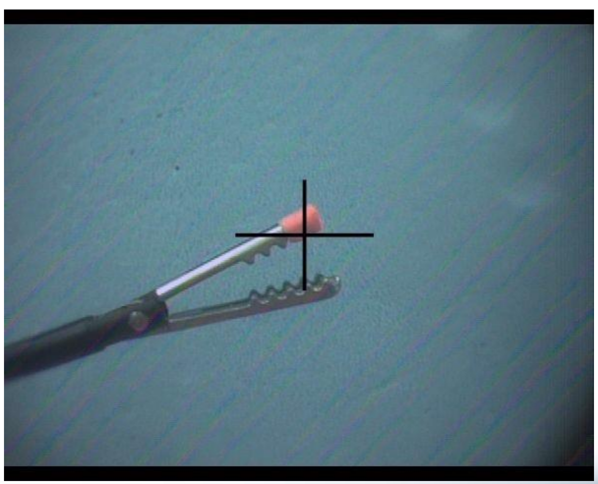
- Allows shared autonomy with surgeon
- The feedback from the tracker can be used to drive motors to keep the tool in the center of the image
- PD controller used
- (E_x , E_y): offset error of tracker from center of image

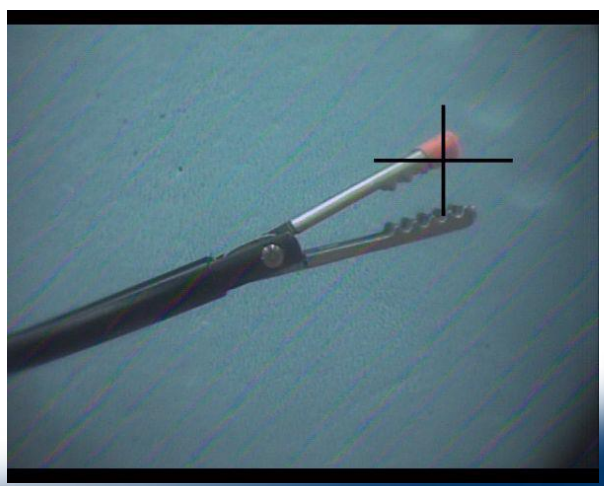
$$\text{Pan speed} \propto (\alpha_x * E_x) - (\beta_x * dE_x/dt)$$

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

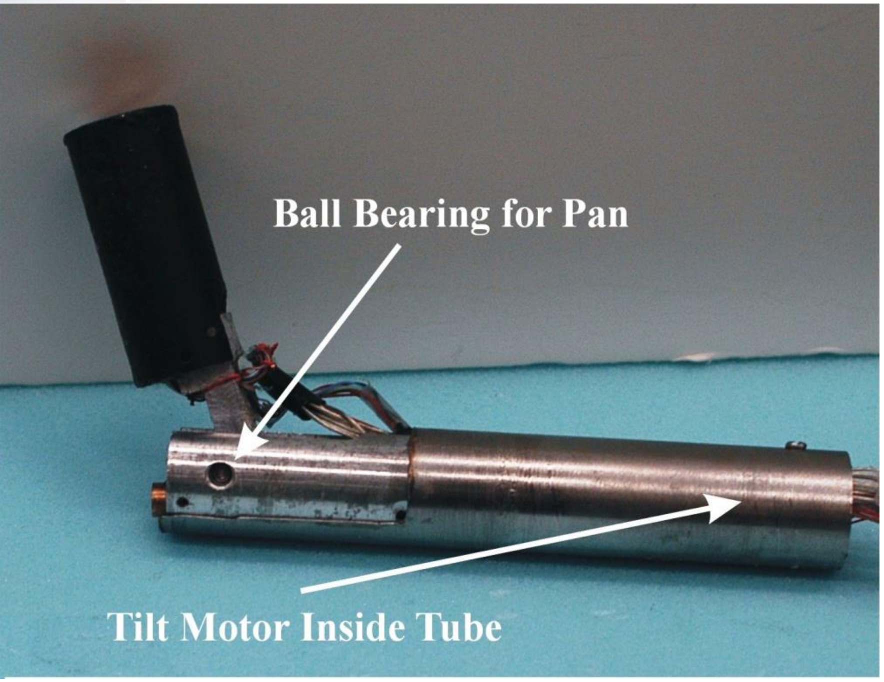
- Video

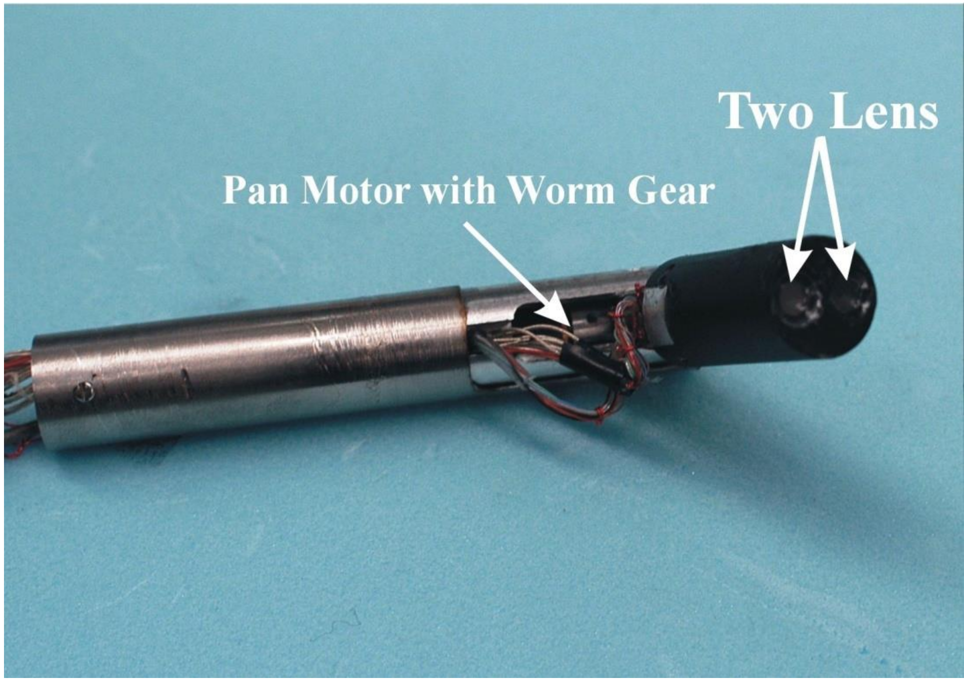






Device III: Stereo Imaging*





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

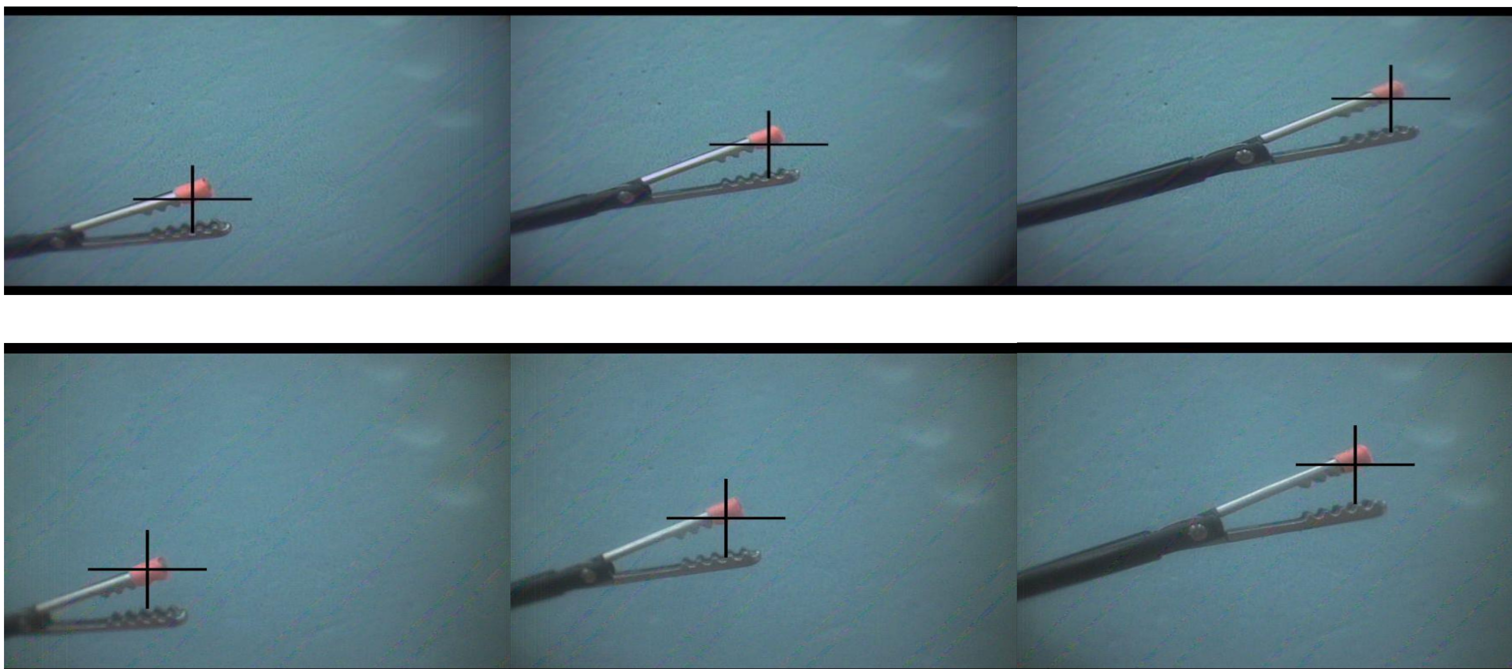
*T. Hu, P. Allen,, T. Nadkarni, N. Hogle, D. Fowler, *Insertable Stereoscopic 3D Surgical Imaging Device*, IEEE BIOROB 2008

Visual Servoing with Stereo

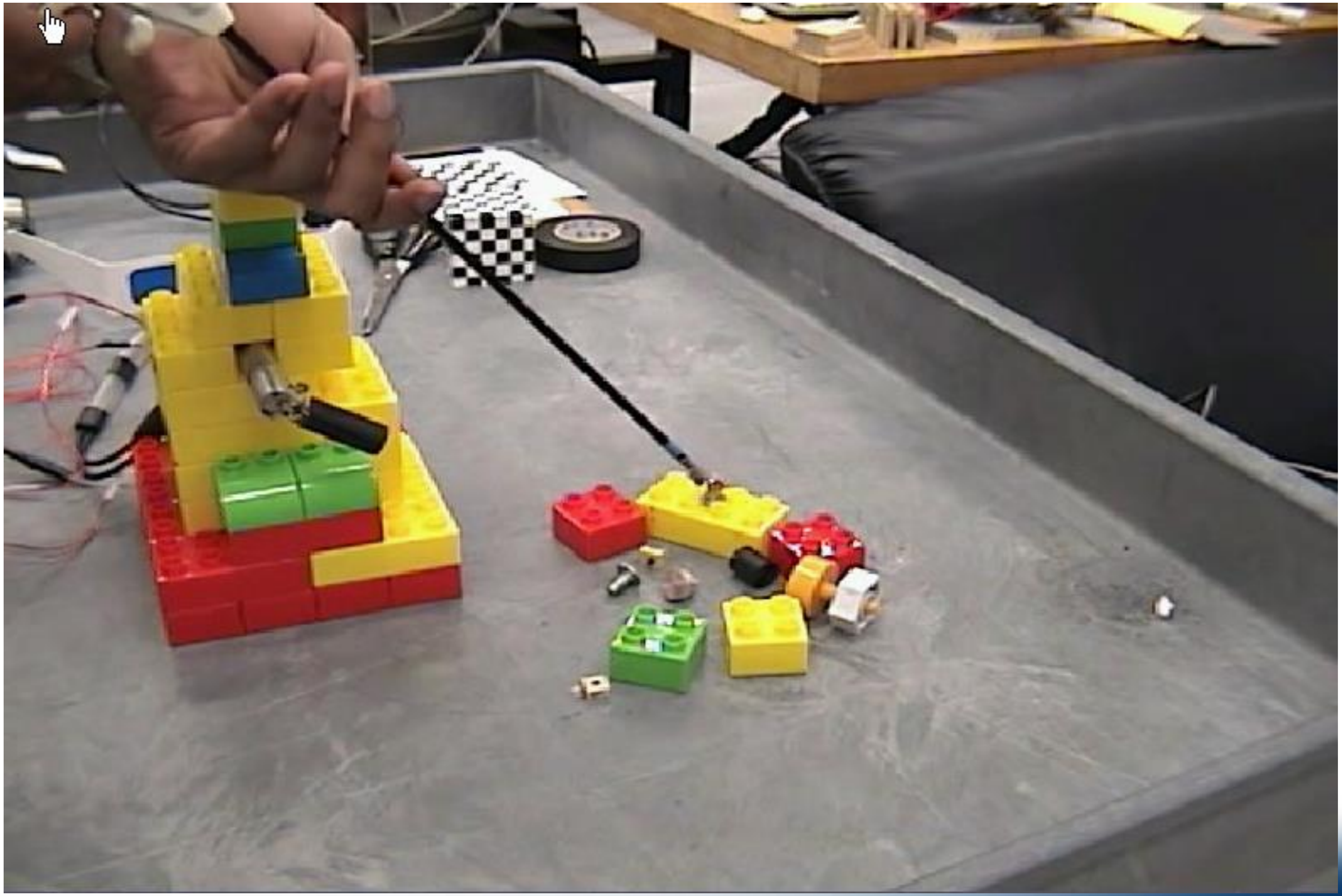
- When using stereo cameras the pixel disparity E_p between stereo images is used to damp the motors

  Speed Damping $\propto$ (γ * E_p)

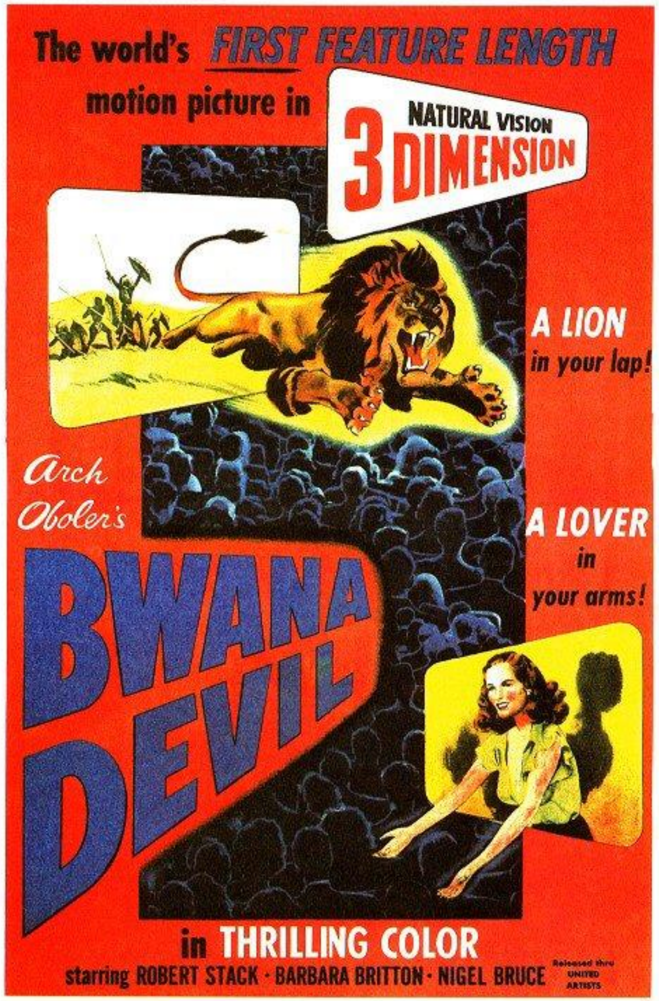
- Damping is applied to both Pan and Tilt motors
- Prevents the motors from oscillating when instrument is too close to camera



Device III: Stereo Imaging



Caution: 3D viewing ahead !

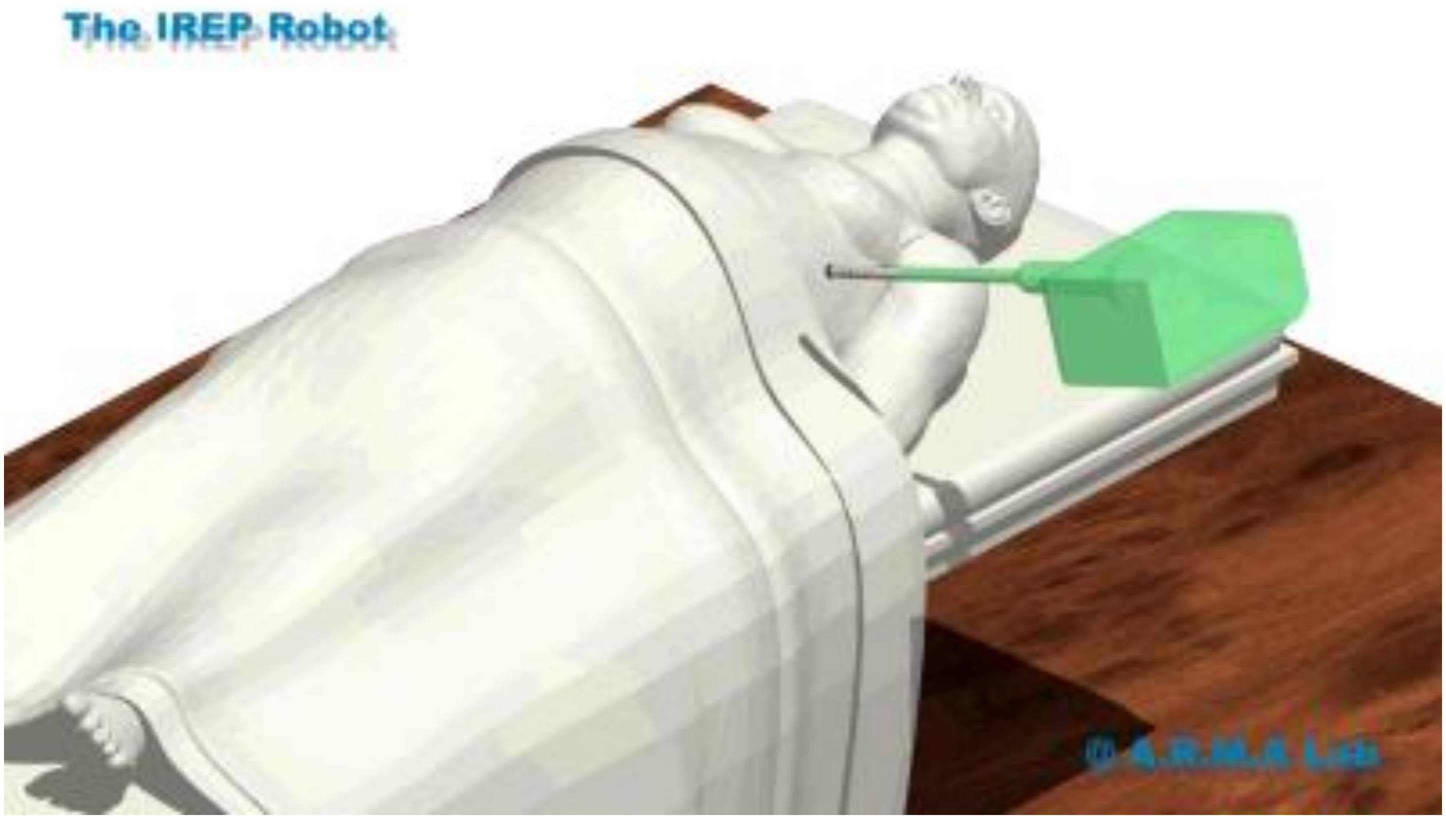


Video 1

Video 2

Automatic Tool Tracking: In-Vivo

Insertable Robotic Effector Platform

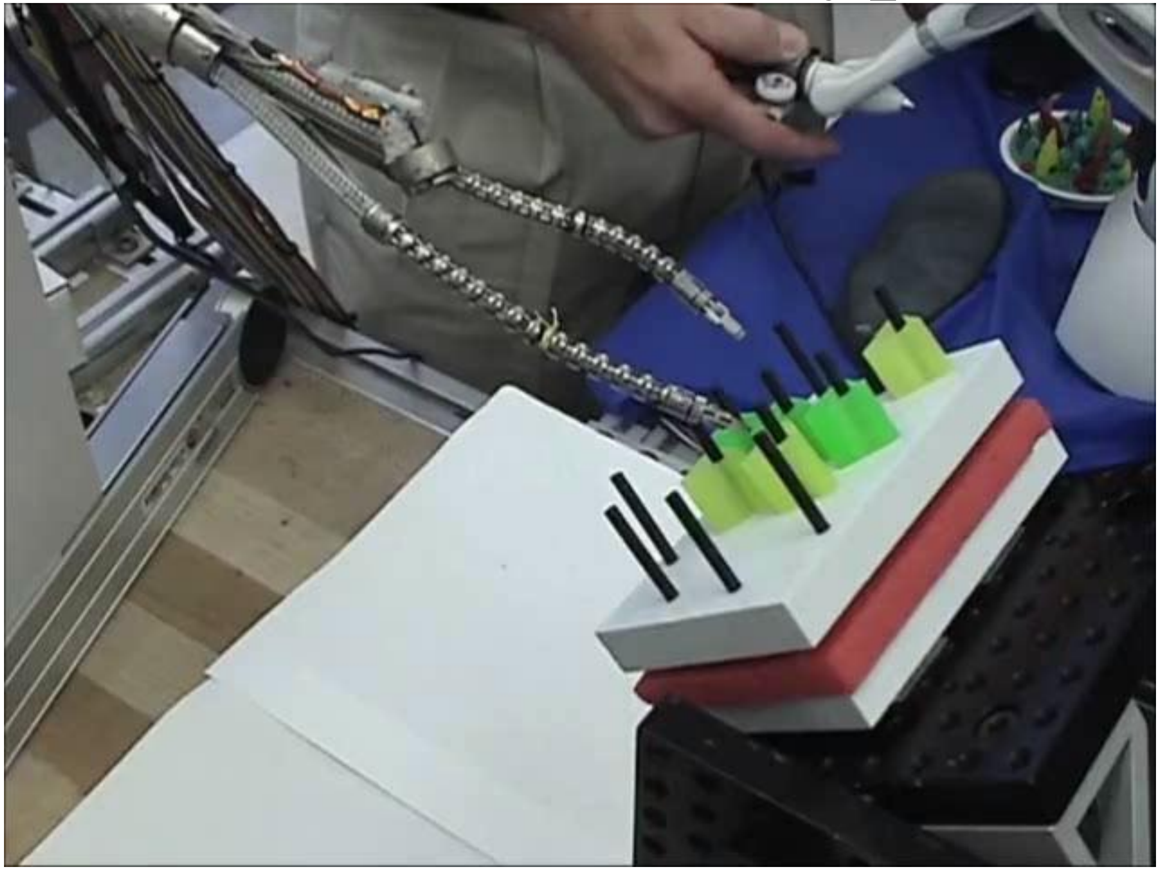


K. Xu, R. Goldman, J. Ding, P. Allen, D. Fowler and N. Simaan, System Design of an Insertable Robotic Effector Platform for Single Port Access (SPA) Surgery, IROS 2009

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

IREP Prototype



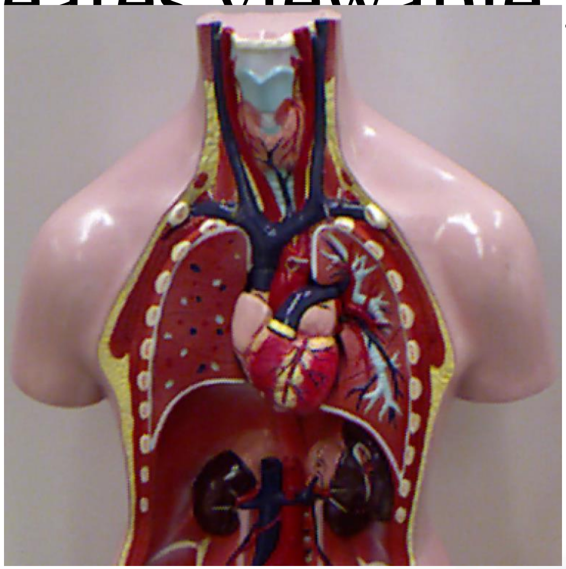
IREP Prototype

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

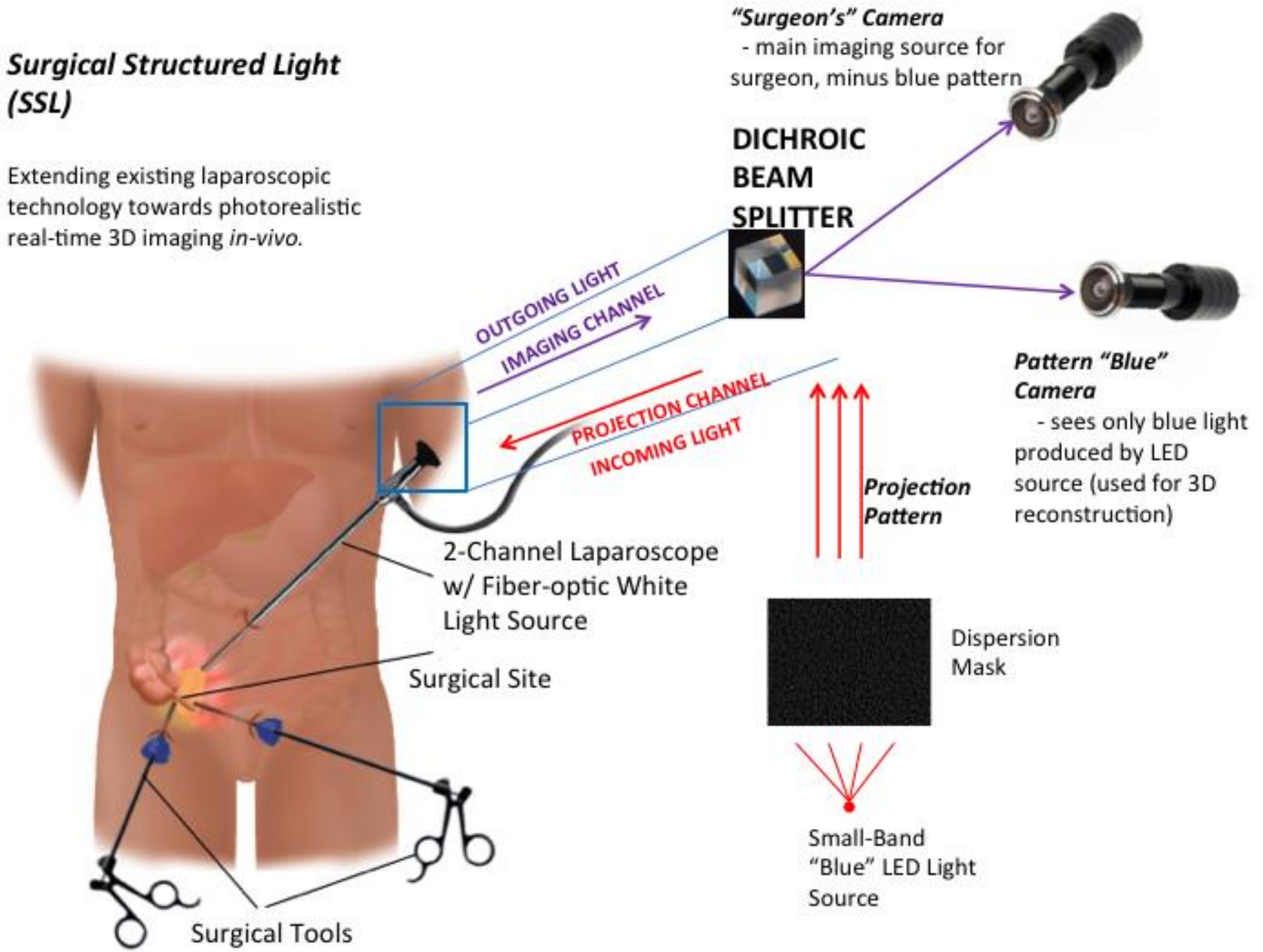
A Single Image:

What we're used to



Fully-rotating 3D display:

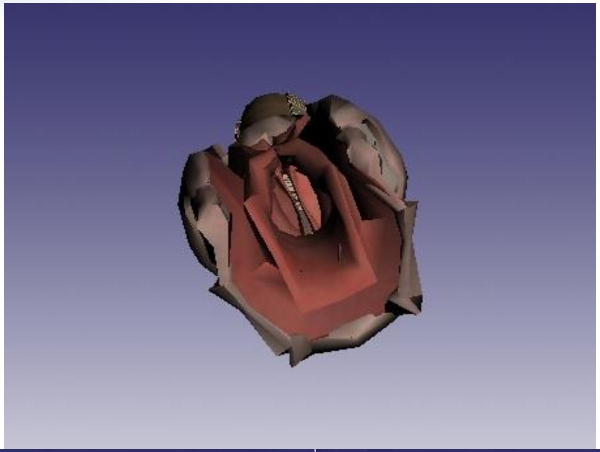
What SSL can provide


Surgical Structured Light (SSL)
Extending existing laparoscopic technology towards photorealistic real-time 3D imaging in-vivo.
"Surgeon's" Camera
- main imaging source for surgeon, minus blue pattern
DICHROIC BEAM SPLITTER
OUTGOING LIGHT
IMAGING CHANNEL
PROJECTION CHANNEL
INCOMING LIGHT
Pattern "Blue" Camera
- sees only blue light produced by LED source (used for 3D reconstruction)
Projection Pattern
2-Channel Laparoscope w/ Fiber-optic White Light Source
Surgical Site
Dispersion Mask
Small-Band "Blue" LED Light Source
Surgical Tools

Virtual Novel Views

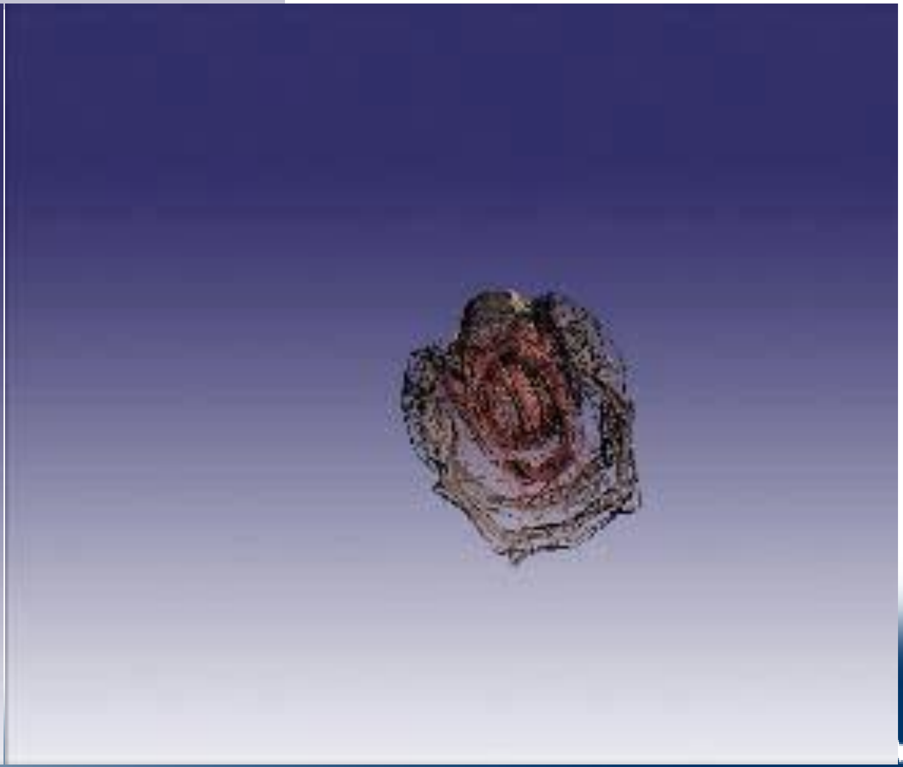
Example: internal anatomy

Not possible with current technology!

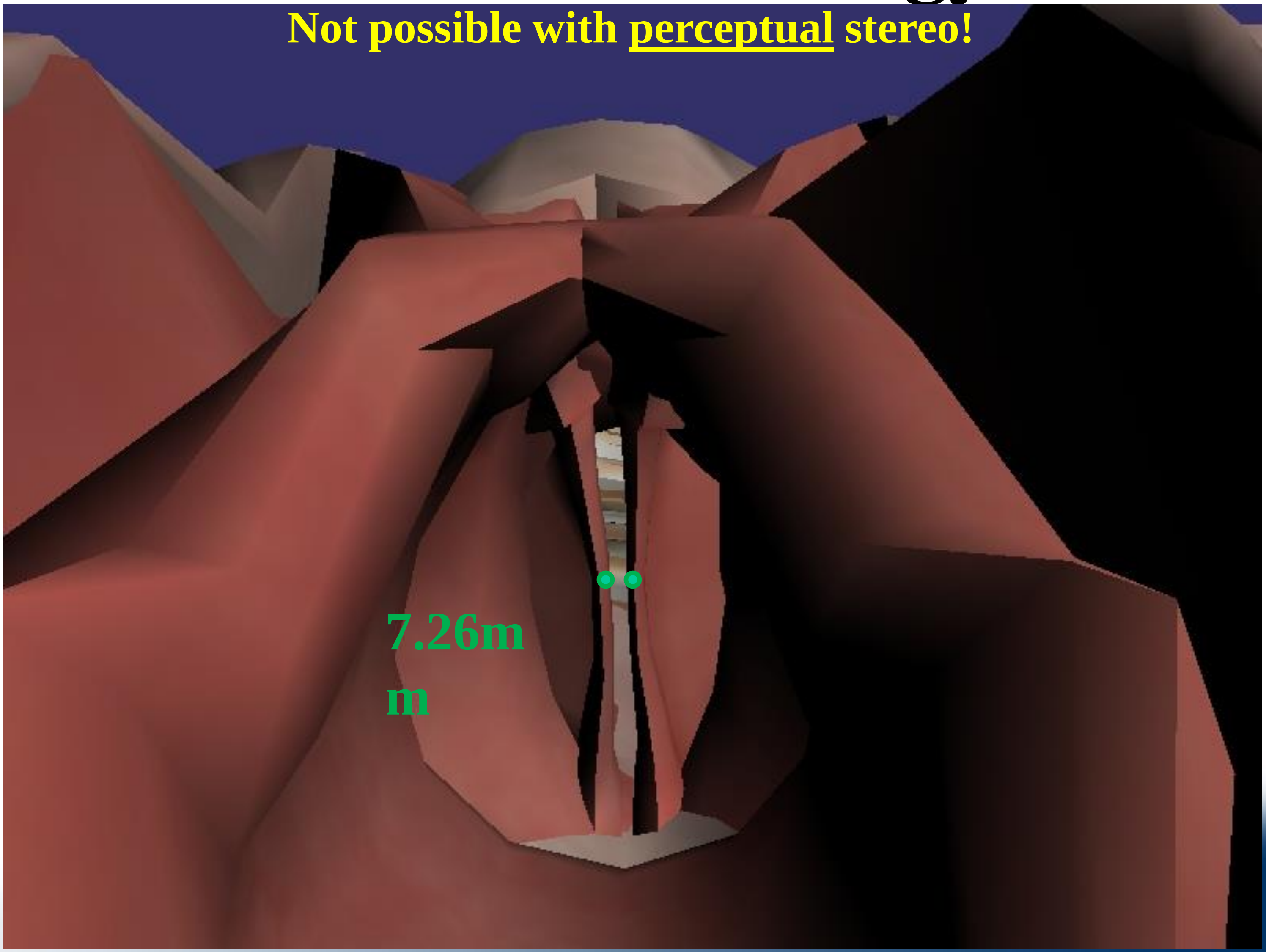


Camera Viewpoint Can Be Limiting

- 3D model allows novel views
- Model can be registered to patient data
- Accurate metrology in-vivo
- 3D “mosaicing” can build model from different viewpoints inside the body

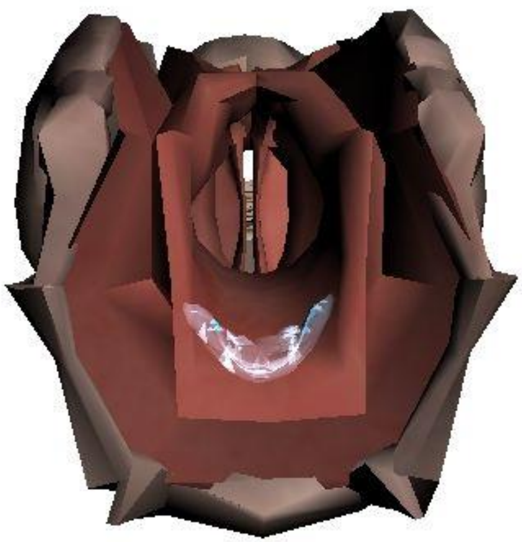


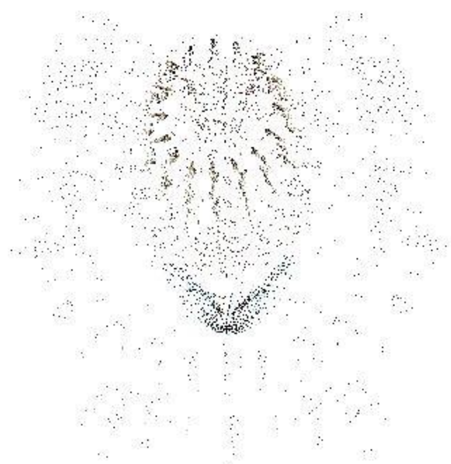
In-Vivo Metrology

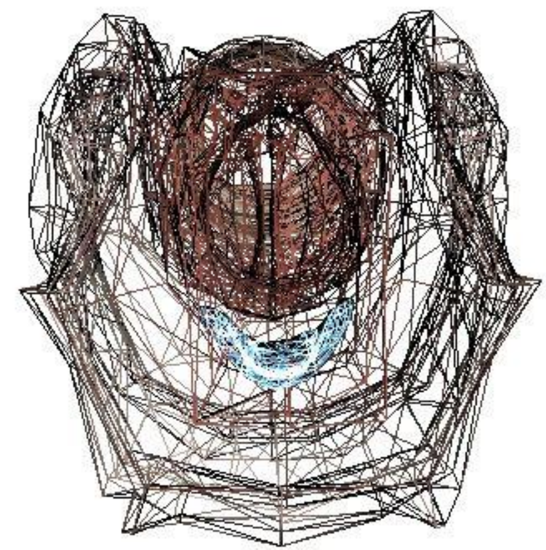


Intra-Operative Registration

MATCH

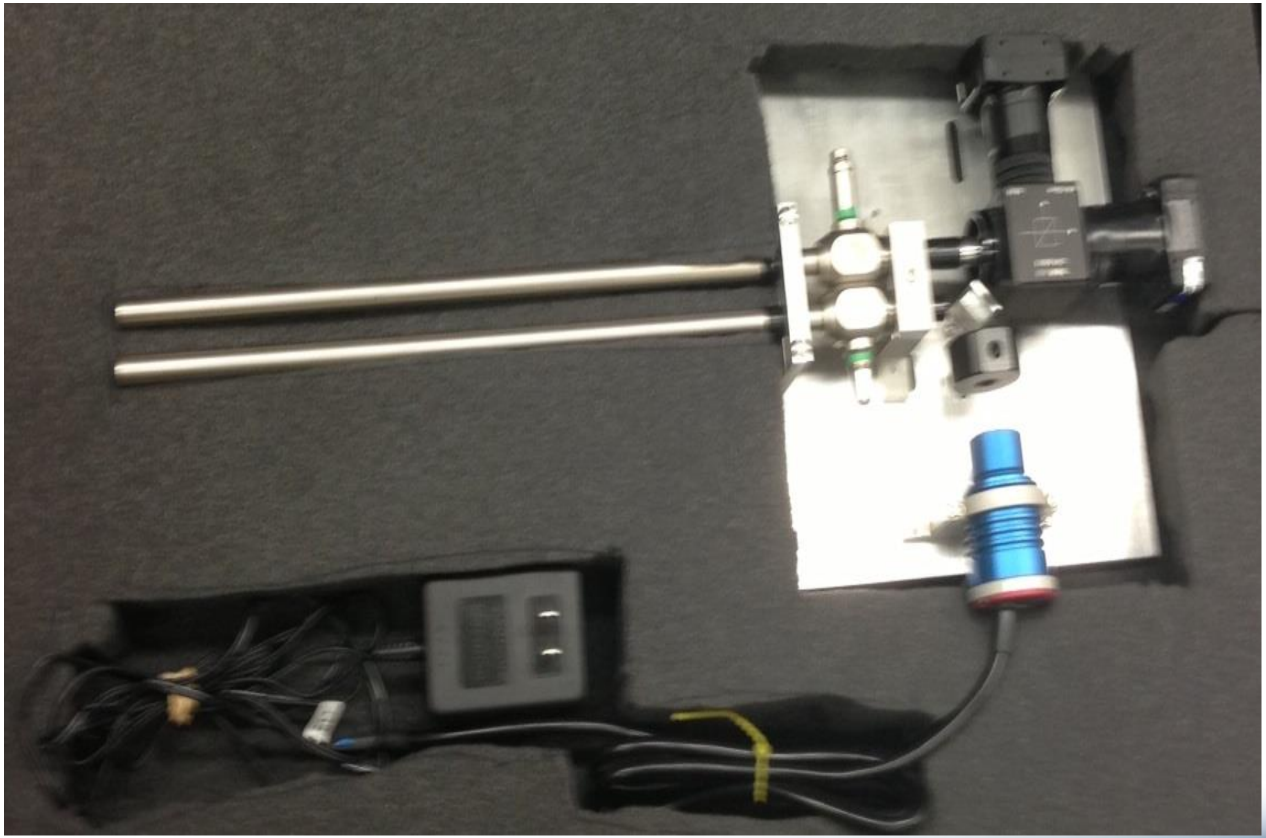


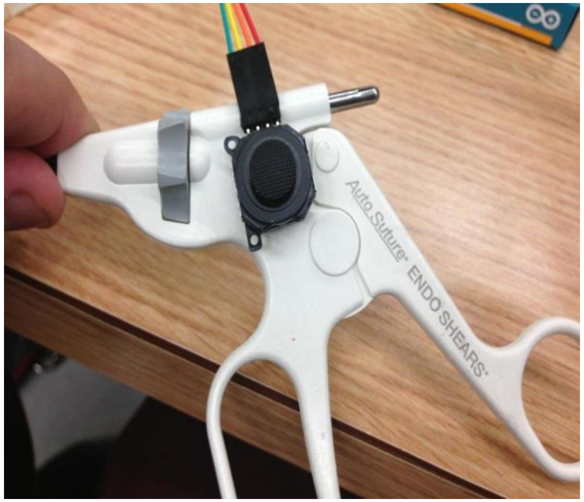




1. **Pre-operative patient anatomy**
2. **Intra-operative extraction of point cloud from**
3. **Software converts to mesh**

SSL Prototype





3D Reconstruction

video

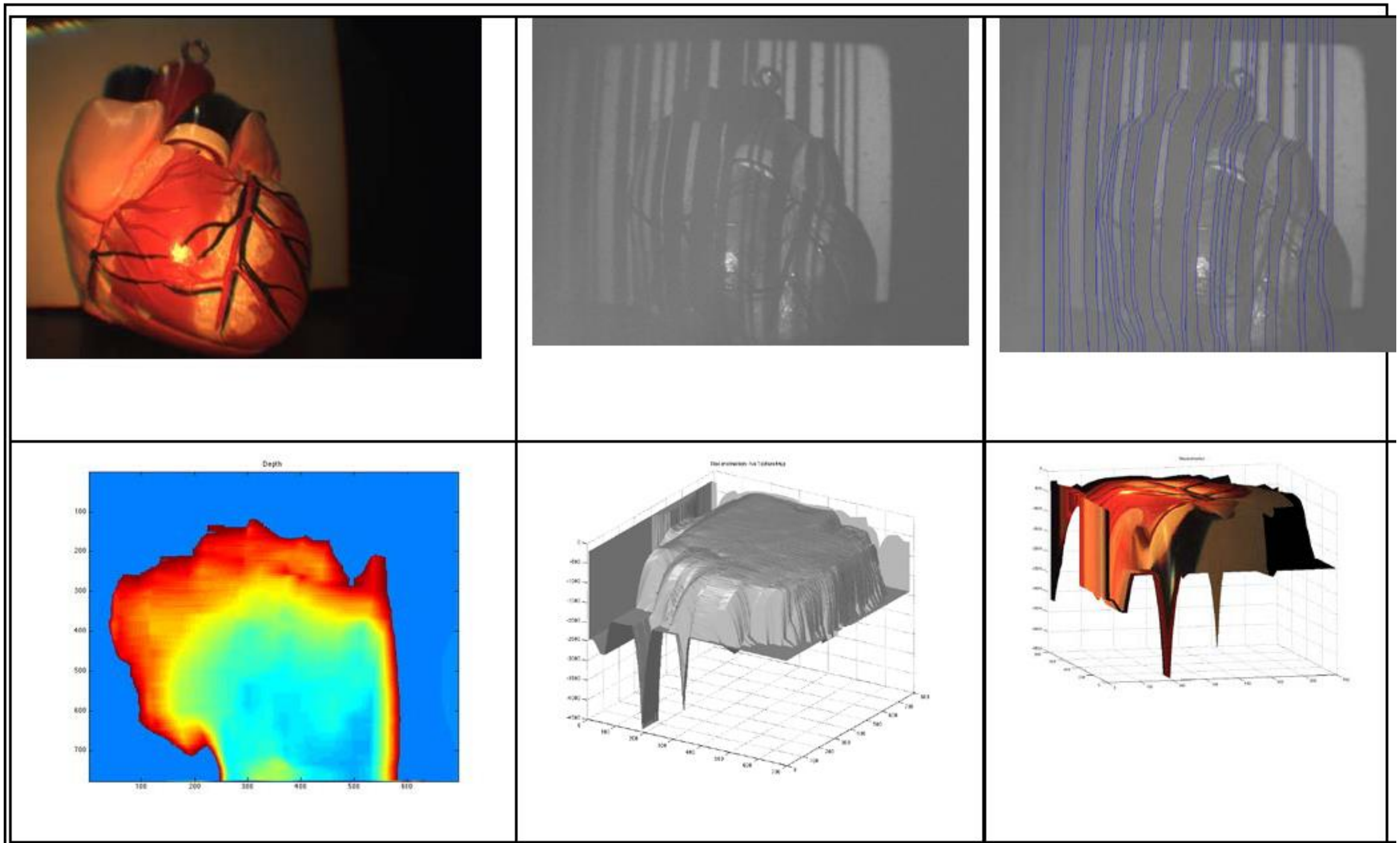


Figure 3: Top row, left to right: a) Plastic heart model image as seen through white light reception camera; b) Structured light image as seen through the blue light reception camera; c) Structured light patterns identified on image. Bottom row, left to right: a) Pseudo color depth map generated from the structured light; b,c) Two views of the 3D model of the reconstructed heart, both without (middle) and with (right) texture mapping.