Spatial orientation

in Natural Orifice Translumenal Endoscopic Surgery

May 4, 2009

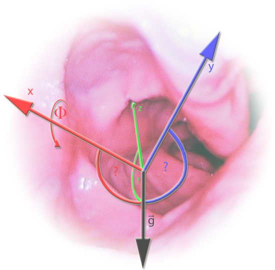
Dipl.-Ing. Kurt Höller

Chair of Pattern Recognition (CS 5)

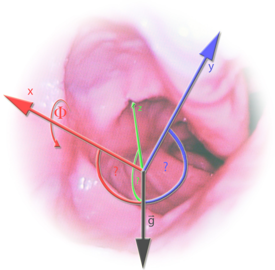
Friedrich-Alexander-University Erlangen-Nuremberg

Germany

Content



Overview



Chair of Pattern Recognition

Friedrich-Alexander-University Erlangen-Nuremberg, Germany

- Head
  - Prof. Dr.-Ing. Joachim Hornegger
- Fields of research
  - Medical image processing
  - Computer vision
  - Speech processing and understanding
  - Digital sports
- Our Staff
  - 4 Professors
  - 50 Researchers
  - 2 Administration Secretaries
  - 2 Laboratory Assistants, 1 Trainee

Background of the MUSTOF project group

Our team: Multiple interests, one vision...

- Organizational and personal infrastructure of the group:
  - computer scientists
  - electrical engineers
  - physicists
  - physicians
- Industrial partners:
  - endoscopy
  - camera
  - software

Figure: In the operation room

Endoscopic 3-D approaches

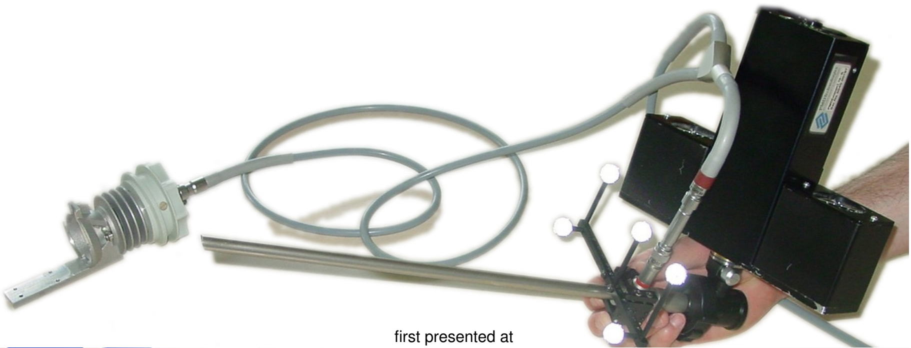
State of the Art

Position or distance information can be achieved with

- endoscopic ultrasound (EUS)
- magnetically anchored instruments
- passive optical approaches
  - stereo vision
  - structure from motion
  - shape from shading
- active optical approaches
  - pattern projection
  - **time-of-flight hybrid system**
- **inertial sensors for gravity related rotation correction**

First prototype of a 3-D endoscope

Based on time-of-flight technology



first presented at

New 'killer-application'

For Multi-Sensor-Time-Of-Flight (MUSTOF) Technology

- We invented a very useful endoscopic tool
- DFG-Sonderforschungsbereich 603 with laparoscopic cholecystectomy was not continued
- We needed a new **killer-application**!

⇒ We found one:

New 'killer-application'

For Multi-Sensor-Time-Of-Flight (MUSTOF) Technology

Figure: NESA, K. Witzel 2006

'Towards NOTES^{3D}'

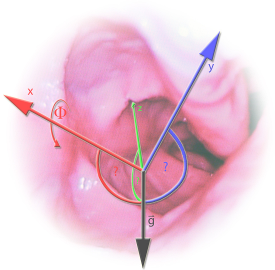
Joint funding application at Deutsche Forschungsgemeinschaft (DFG)

Participating institutes:

- LME, Erlangen (Prof. J. Hornegger)
- MITI group, Munich (Prof. H. Feussner)
- CAMP, Munich (Prof. N. Navab)
- LGDV, Erlangen (Prof. G. Greiner)
- MED1, Erlangen (Prof. E.G. Hahn)

Submitted during

Overview



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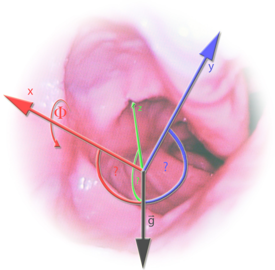


Time Line

From open surgery to NOTES

Surgery can be done as:

- open surgery
  → for hundreds of years
- minimally invasive / laparoscopic surgery
  → since the late 80s
- and through natural orifices
  → "no longer if but when" (W. O. Richards, D. W. Rattner 2005)

⇒ July 22/23, 2005 white paper and foundation of Consortium for Assessment and Research (NOSCAR) on NOTES: Natural Orifice Translumenal Endoscopic Surgery

NOTES Timeline

Starting

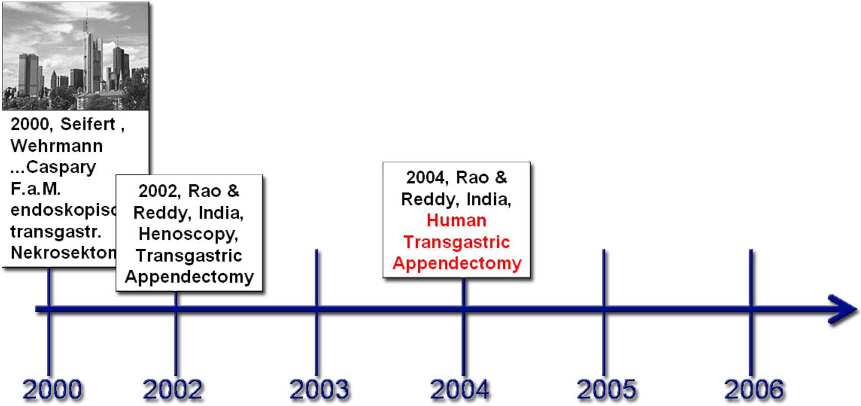


Figure: D-NOTES 2007 Mariensee (W. Lamadé, J. Hochberger)

First human NOTES procedure

2004, Rao and Reddy, India

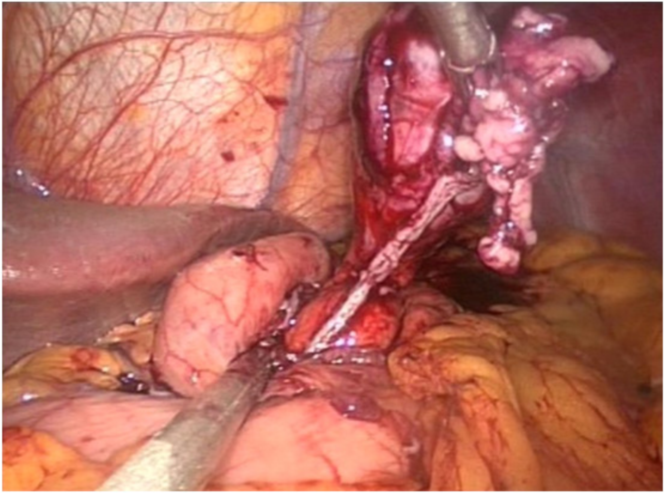


Figure: First Human NOTES appendectomy (RAO and Reddy 2004)

Participating groups with NOTES

Great chance for technical innovations

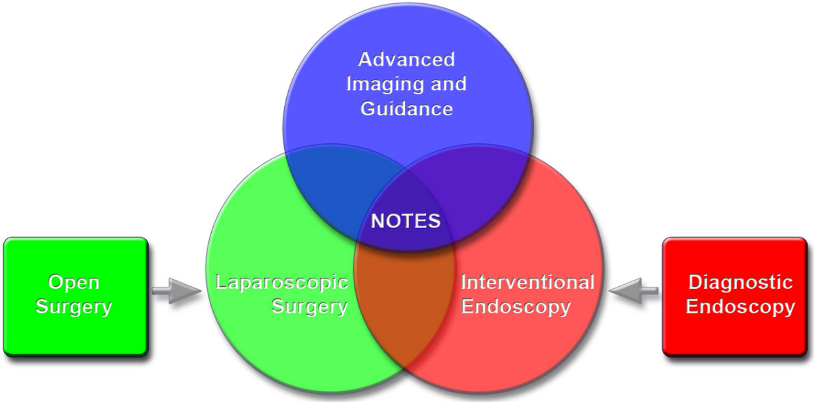


Figure: Interdisciplinarity of Natural Orifice Translumenal Endoscopic Surgery (NOTES)

Benefits

Of Natural Orifice Translumenal Endoscopic Surgery (NOTES)

Expected benefits of NOTES:

- Less pain
- Faster recovery
- Better cosmetic results avoiding skin incisions
- Lower risk for herniation
- No risk for eventration
- Lower risk for adhesions
- Potentially lower risk for wound infection

Improvements

With Natural Orifice Translumenal Endoscopic Surgery (NOTES)

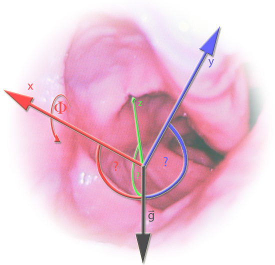
Expected improvements with NOTES:

- significantly shortened patients' hospital stays
- no sterile operating room (only instruments)
- new dimension for medical care in developing countries

There will be better help for

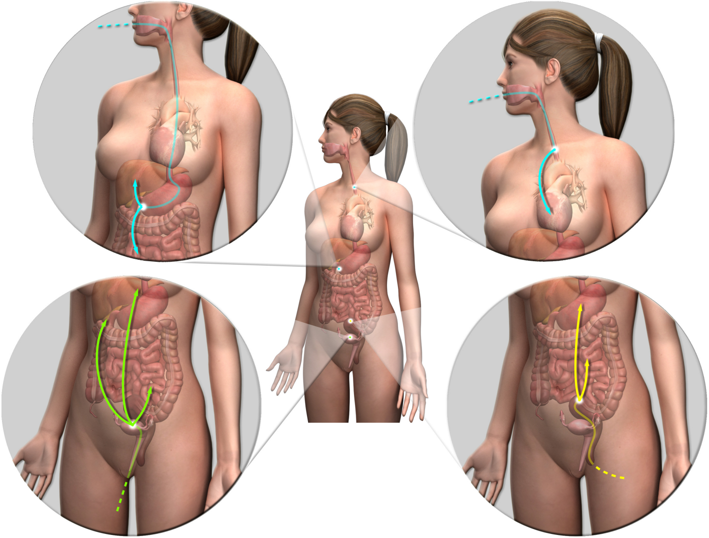
- obese patients
- burn injuries
- children

Overview



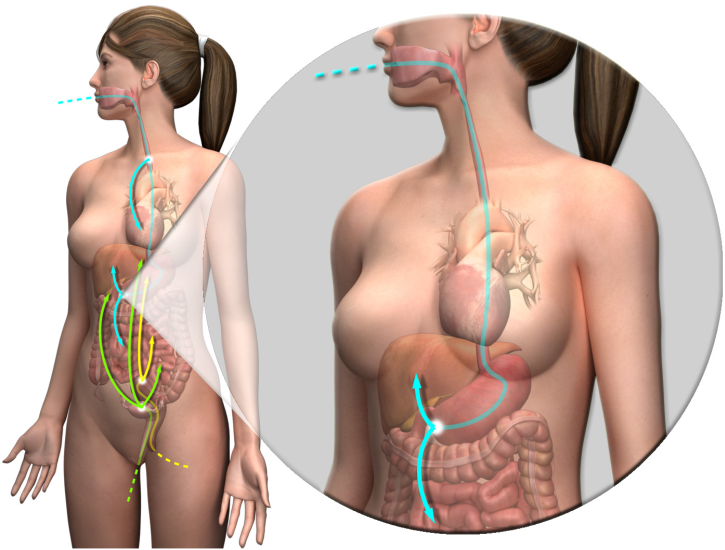
Routes through natural orifices

Natural Orifice Translumenal Endoscopic Surgery



Peroral transgastric route

Natural Orifice Translumenal Endoscopic Surgery



Flexible endoscope through wall of stomach

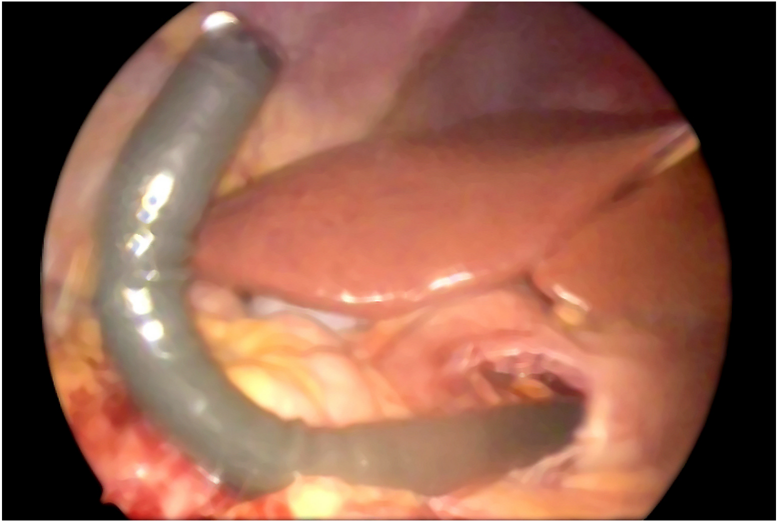
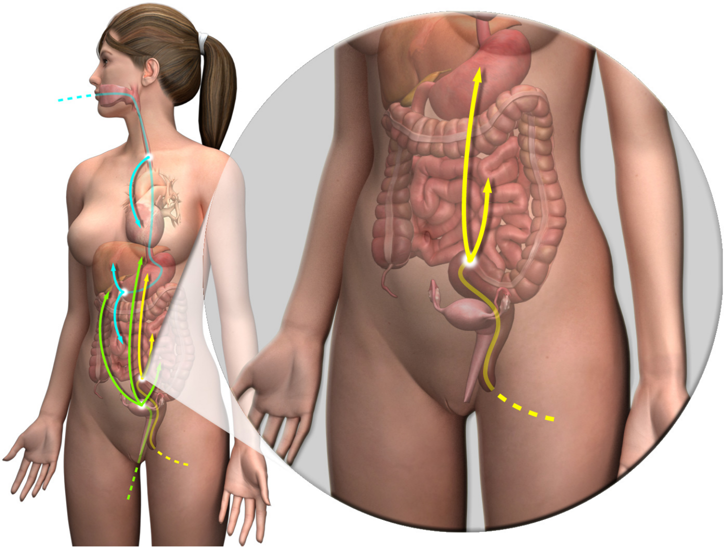


Figure: Resection of gastric stromal tumor (J.L. Ponsky 2006)

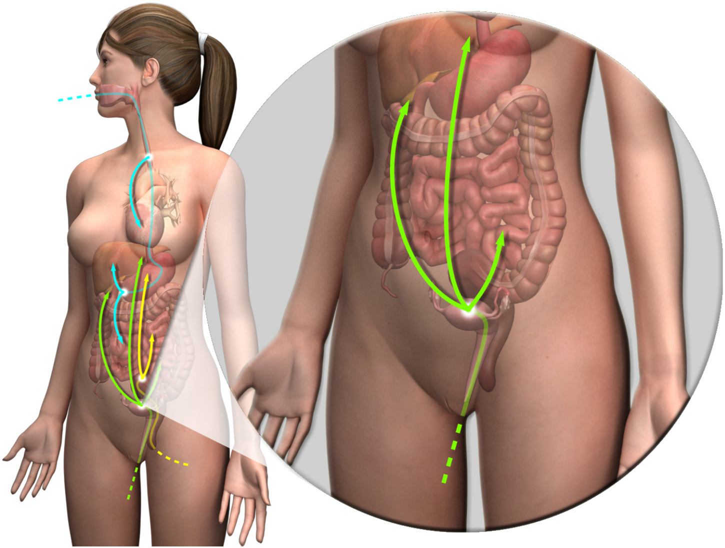
Peranal transcolonic route

Natural Orifice Translumenal Endoscopic Surgery



Transvaginal route

Natural Orifice Translumenal Endoscopic Surgery

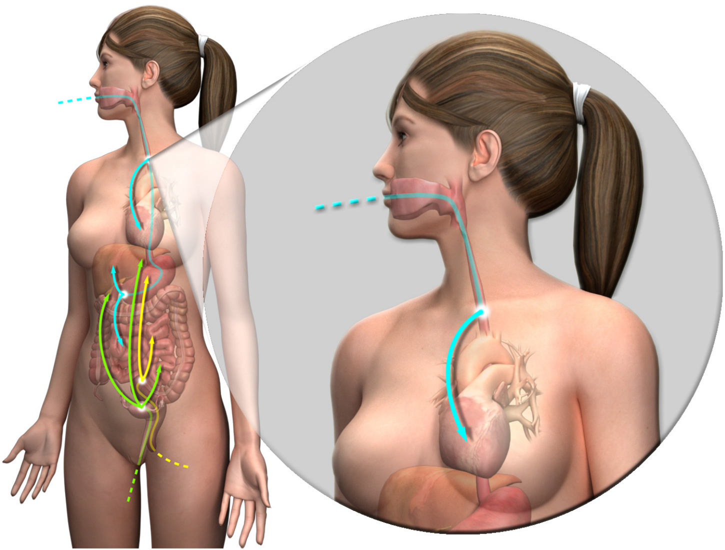


Transvaginal route

Figure: Transvaginal Cholecystectomy (R. Zorron, Strasbourg 2007)

Peroral transesophageal route

Natural Orifice Translumenal Endoscopic Surgery



Transesophageal access to the heart

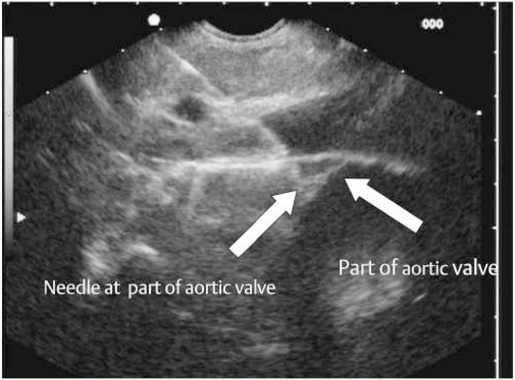


Figure: Transesophageal endoscopic ultrasound-guided access to the heart. The EUS needle after penetration into the left atrium, placed at one leaflet of the aortic valve (A. Fritscher-Ravens 2007).

Possible therapies

Using NOTES technique

First discussed and tried therapies with NOTES:

- liver biopsy (2004)
- tubal ligation (2005)
- cholecystectomy (2005)
- oophrectomy (2005)
- partial hysterectomy (2005)
- gastrojejunostomy (2005)
- lymphadenectomy (2006)
- appendectomy

Figure: Oophrectomy (Wagh 2005)

Possible therapies
Using NOTES technique

Some more actual discussed and tried therapies with NOTES:

- splenectomy (2006)
- nephrectomy
- hernia repair
- hepatectomy
- gastrectomy
- bypass surgery
- peritoneal biopsy
- heart biopsy
- retreatment of diverticulosis fistulae

Figure: Splenectomy (Kantsevoy 2006)

NOTES Publications 2004-2008

Fast growing community

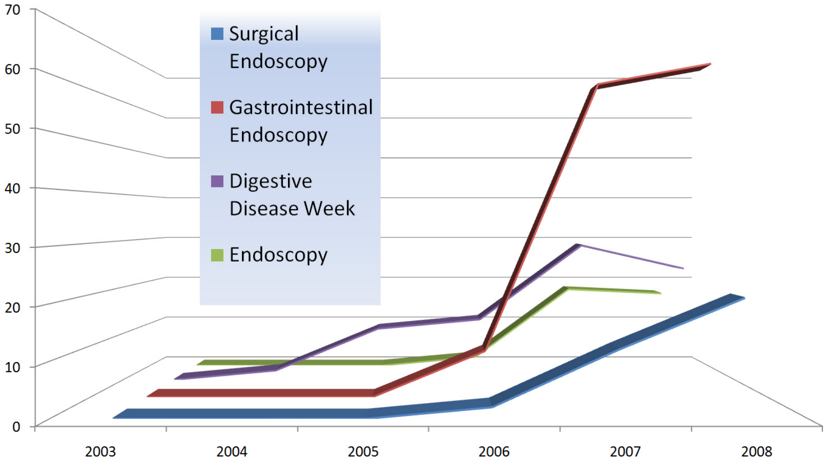
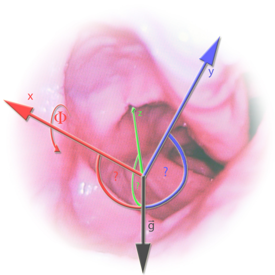


Figure: NOTES Publications in SE (SAGES), GIE (ASGE), Endoscopy (ESGE), DDW

Overview



Access: Keeping the bowel loops apart using fluid

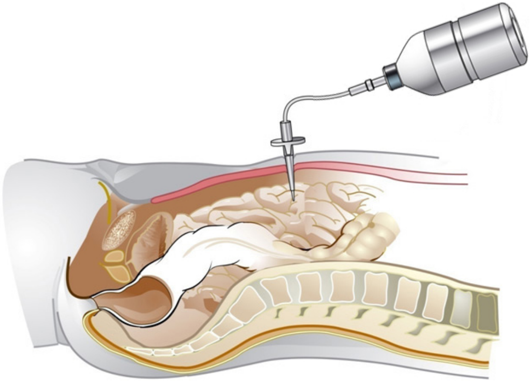


Figure: ISSA for NOTES (D. Wilhelm, A. Meining, A. Schneider, H. Feussner 2007): Lifting Colon

Access: Encircing by a purse string suture

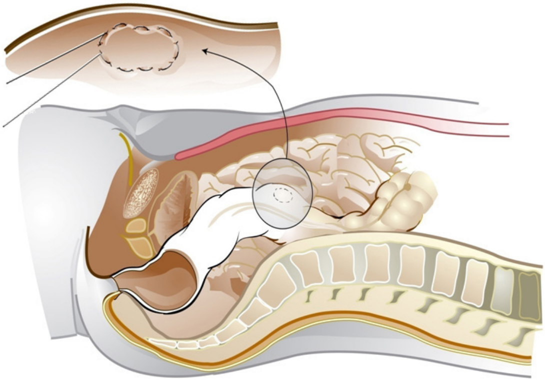


Figure: ISSA for NOTES (D. Wilhelm, A. Meining, A. Schneider, H. Feussner 2007): Purse string suture

Access: Sterilized trocar inserted by perforating the area of rectal wall

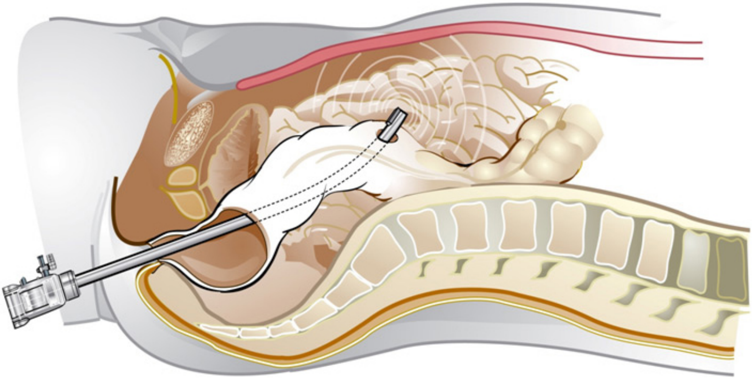


Figure: ISSA for NOTES (D. Wilhelm, A. Meining, A. Schneider, H. Feussner 2007): A flexible endoscope can be passed through the sterile interior of the trocar

Access: Inserting the endoscope through the trocar

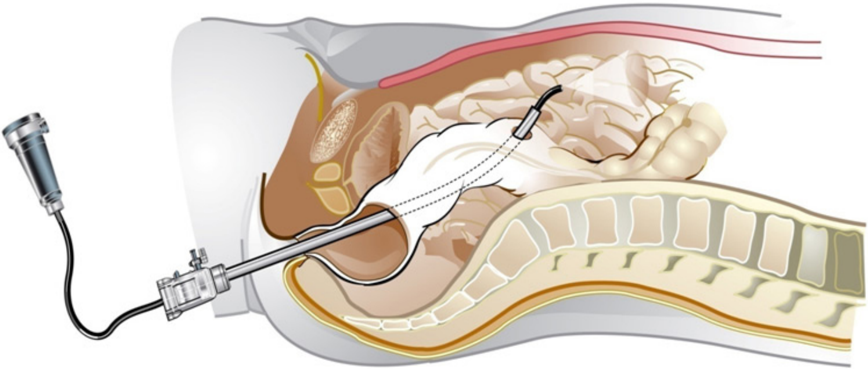


Figure: ISSA for NOTES (D. Wilhelm, A. Meining, A. Schneider, H. Feussner 2007)

Access: Purse string suture is immediately closed after withdrawal of the trocar

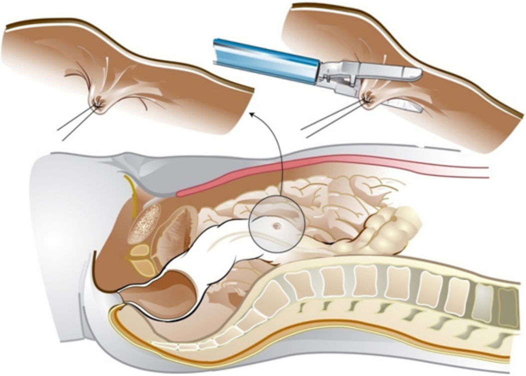


Figure: ISSA for NOTES (D. Wilhelm, A. Meining, A. Schneider, H. Feussner 2007): One or two applications of the linear stapling device

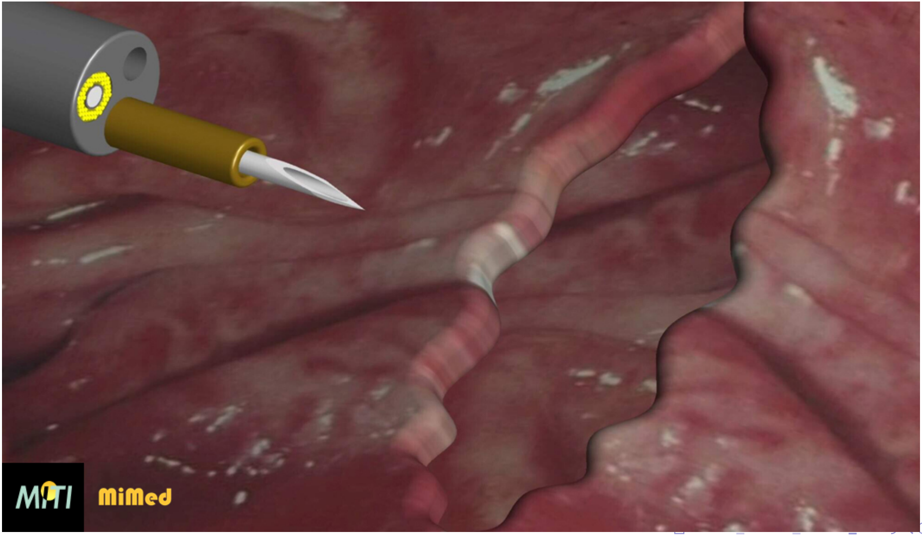
Closure of the access to the abdominal cavity

Gastric or colonic wall incision can be closed using

- Endoclips
- Stapler
- Suturing devices
- Anastomotic devices

Closure of gastric or colonic wall incision (MITI)

Endoclips, H. Feussner 2006



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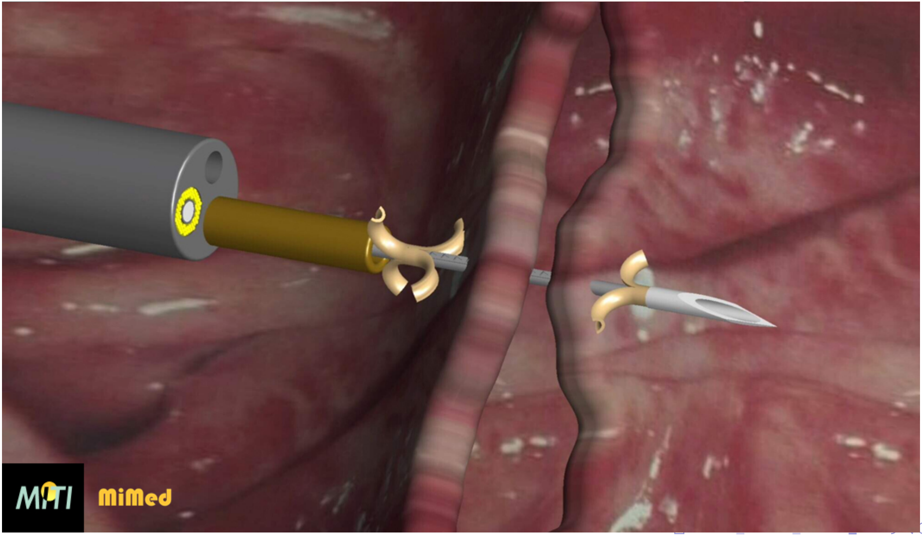

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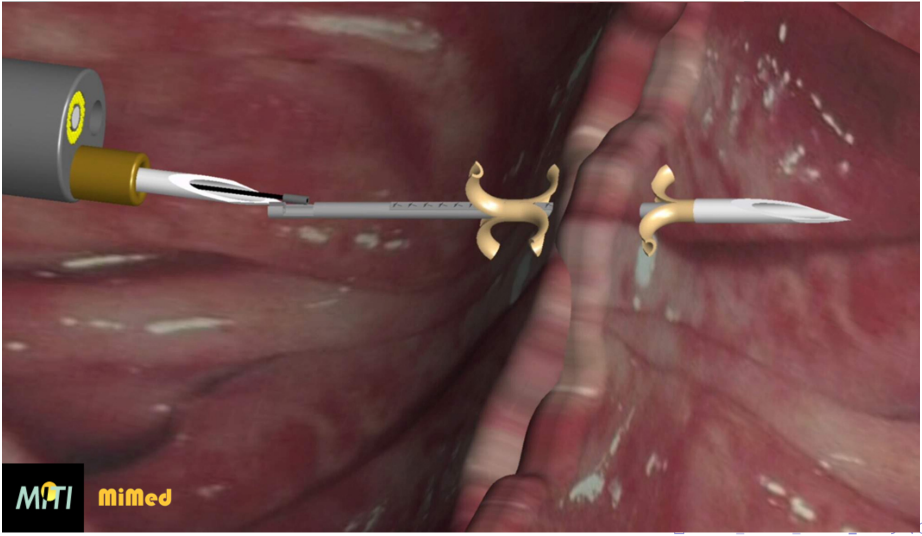

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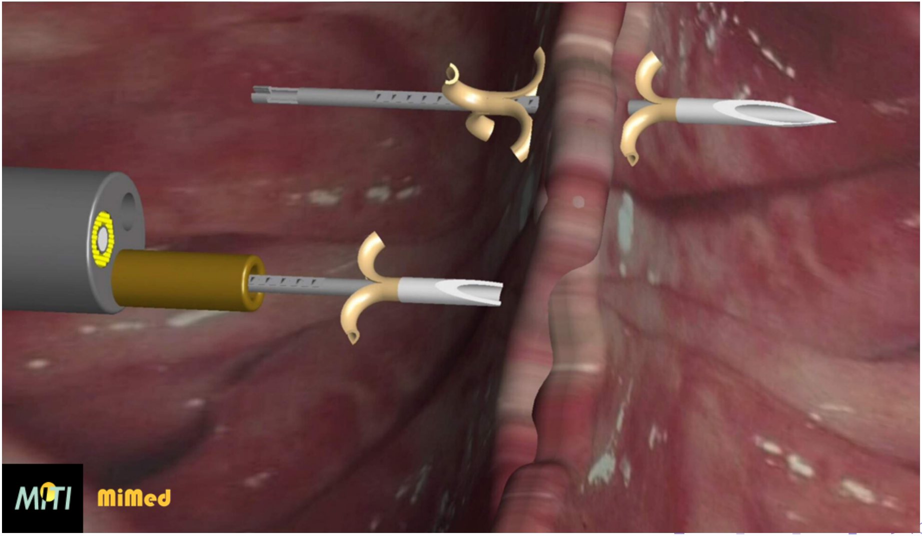
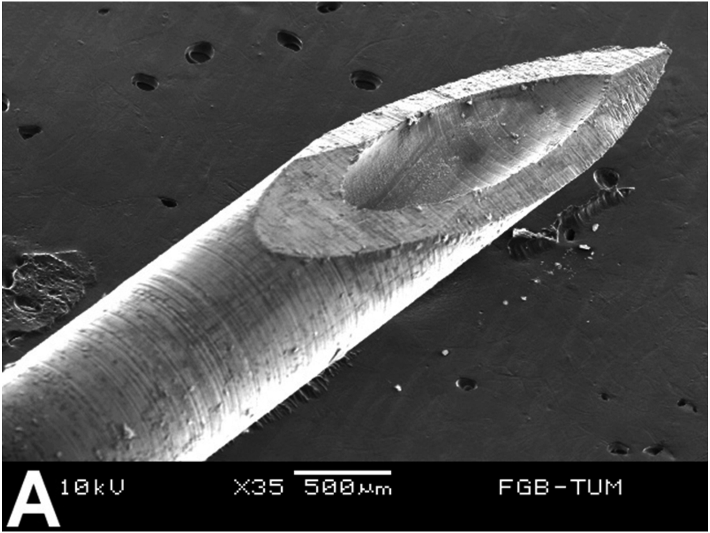


Closure of gastric or colonic wall incision (MITI)

dissolving magnesium spike, H. Feussner 2006



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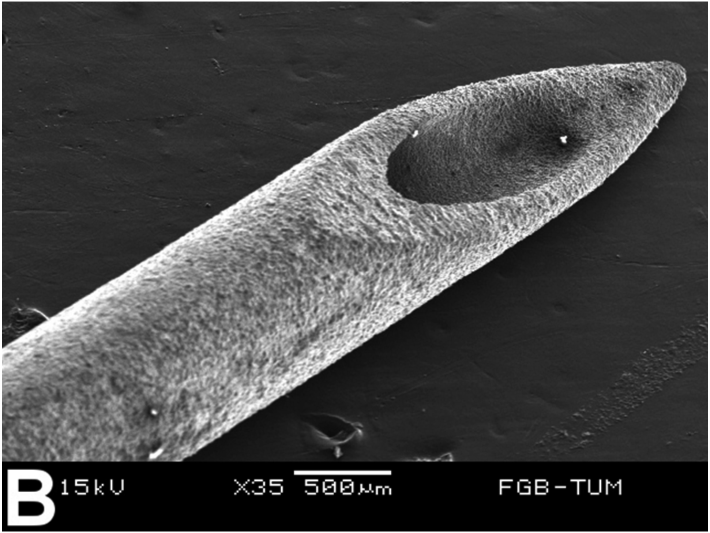

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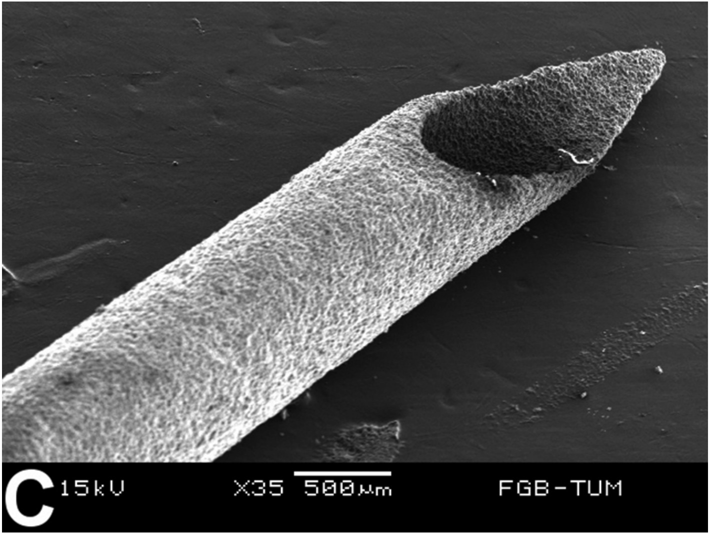


Stapling devices

Figure: Kaehler: Endoscopic stapler

Suturing devices

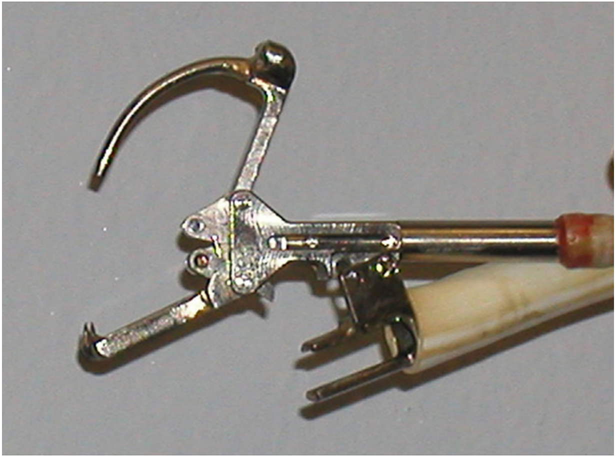
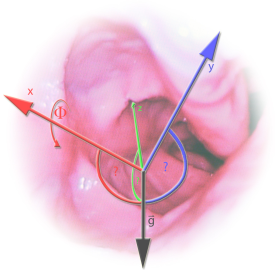


Figure: Olympus 'Eagle Claw'

Suturing devices

Figure: USGI Medical: G-Prox

Overview



Potential barriers to clinical practice

According to the NOTES white paper, New York 2005

Fundamental challenges to the safe introduction of NOTES

- Access to peritoneal cavity
- Gastric or intestinal closure
- Prevention of infection
- Development of suturing and anastomotic (nonsuturing) devices
- Maintaining spatial orientation
- Development of a multitasking platform
- Management of intraperitoneal complications and hemorrhage
- Physiologic untoward events
- Training other providers

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Development of a multitasking platform

Requirements

Multiple surgery devices and data sources require

- multiple visualization systems:
  - HMD, stereoscopic monitors
  - augmented reality
  - virtual mirror
  - virtual shadows / illumination
- multiple control systems:
  - voice control
  - gesture control
- computer assisted robotic systems

Development of a multitasking platform: NOTES^{3D}

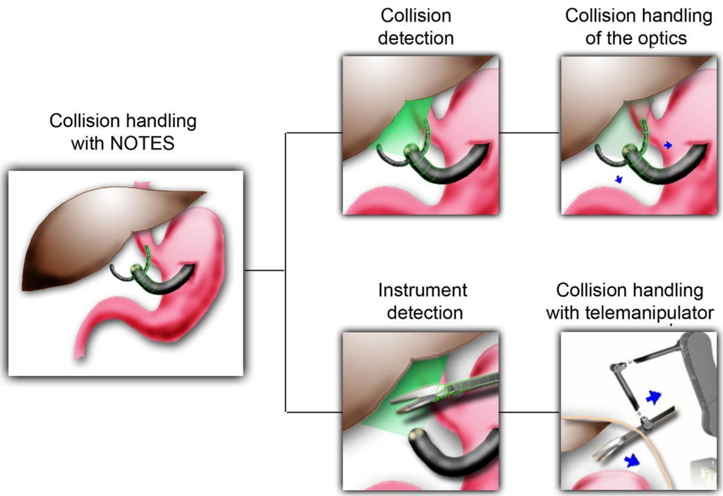
NOTES procedures supported by additional MUSTOF 3-D information

For secure work with computer assisted robotic systems we can support solutions for really important features:

- collision prevention
- motion compensation
- automatic positioning of surgery tools
- image reconstruction for a wider field of view
- virtual rotation of image plane out of the co-axial line

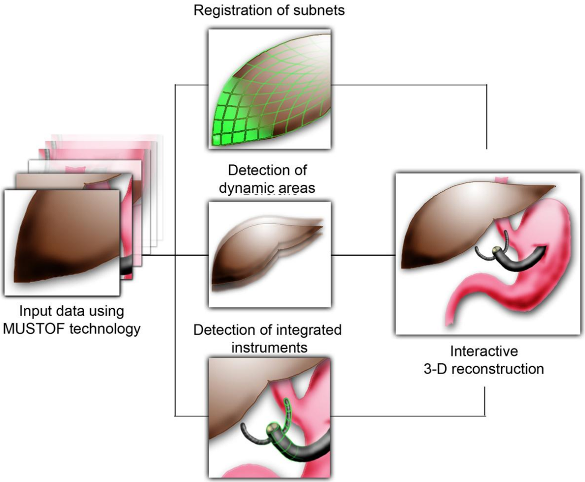
Collision prevention

Paketantrag 'Towards NOTES^{3D}'



Dynamic reconstruction

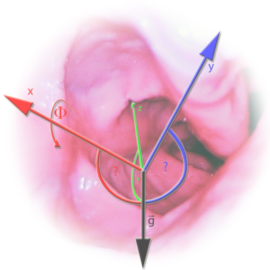
Paketantrag 'Towards NOTES^{3D}'



Development of a multitasking platform

As it could look like

Overview



State of the Art: PMDvision 3kS

Time-of-Flight (ToF) technology

- Lateral resolution: 64×48 pixel
- Depth resolution: 3 mm
- Wavelength: 870 nm
- Pixel dimension: $40\mu m \times 40\mu m$
- Modulation frequency: $20 - 30MHz$ ($\Rightarrow \lambda = 15 - 10m$)
- Frame rate: >15 fps

Figure: ToF-camera and example images

State of the Art

Time-of-Flight (ToF) technology

- Lateral resolution: 176×144 pixel
- Depth resolution: 2,5 mm
- Wavelength: 870 nm
- Pixel dimension: $40\mu m \times 40\mu m$
- Modulation frequency: $20MHz$ ($\Rightarrow \lambda = 15m$)
- Frame rate: >25 fps

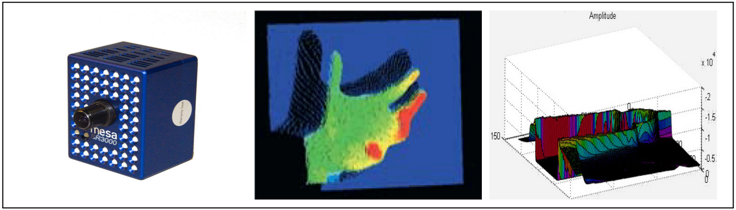


Figure: ToF-camera and example images

March 1st, 2009: PMDvision Cam Cube

Time-of-Flight (ToF) technology

- Lateral resolution: 204×204 pixel
- Depth resolution: 3 mm
- Wavelength: 870 nm
- Pixel dimension: $40\mu m \times 40\mu m$
- Modulation frequency: $20 - 40 MHz$ ($\Rightarrow \lambda = 15 - 7.5m$)
- Frame rate: >15 fps

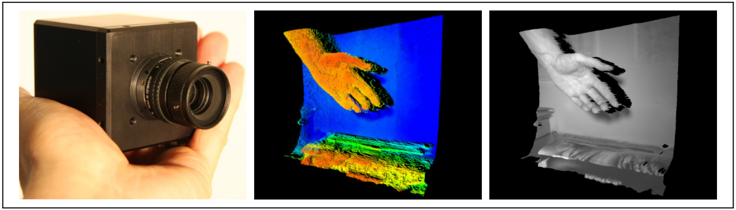


Figure: ToF-camera and example images

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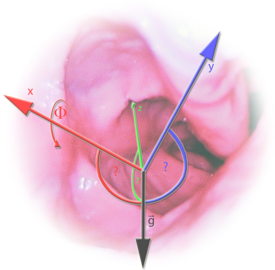
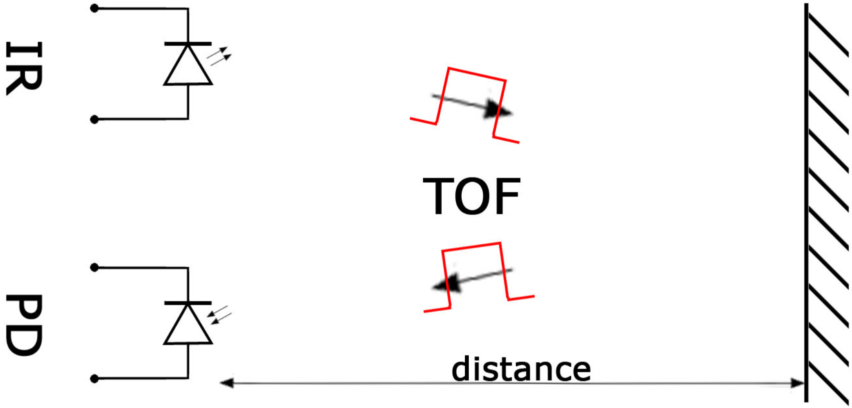


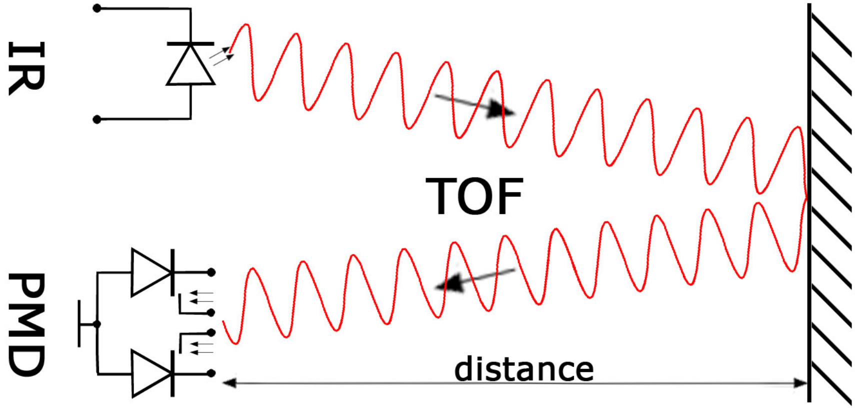
Time-of-flight principle

Pulsed modulation



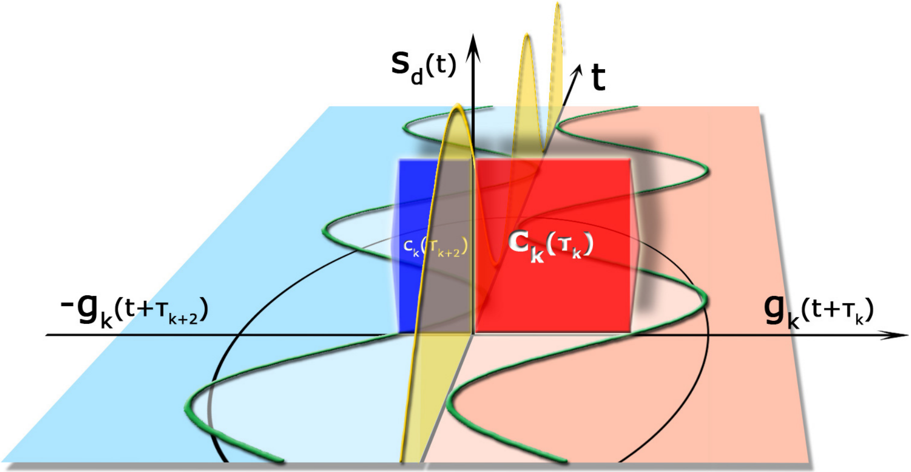
Time-of-flight principle

Continuous wave modulation



"Ladungsschaukel"

charging swing



ToF accuracy

Illumination requirements

- small light emitting surface
- high power
- fast modulation
- narrow-band for ambient light suppression

$$\text{accuracy} \sim \frac{c}{2f_{mod}} \cdot \sqrt{\frac{P_{mod} + P_{amb}}{P_{mod}^2} \frac{A}{k_{opt} q_e r T}}$$

c :	relative speed of light	k_{opt} :	optical system constant
f_{mod} :	modulation frequency	q_e :	quantum efficiency
P_{laser} :	power of modulated signal	r :	target reflectivity
P_{amb} :	ambient light power	T :	integration time
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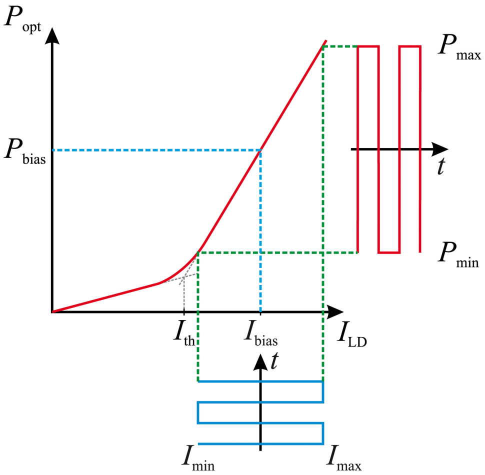
Laser diode modulation

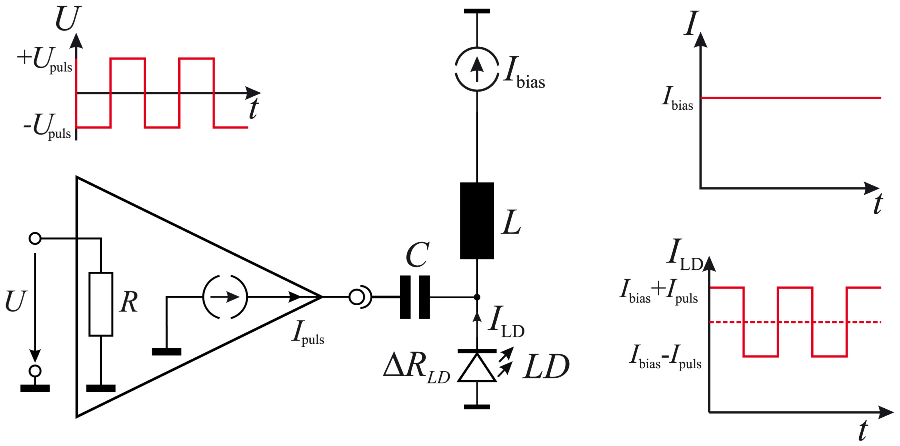
nonlinear characteristics

- fast modulation up to 500MHz
- high power
- differential resistance
- threshhold current between spontaneous and stimulated emission
- linear mode in the range of I_{min} to I_{max}

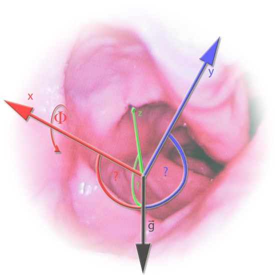


Illumination with Laser Diode and Bias-Tee

Signal with fast modulation (up to 60MHz) and high current (up to 2.25A)



Overview



A simple problem?

Making an endoscope *see 3-D*

- Idea: combine ToF-technology and endoscope optic to enable 3-D reconstruction of operation area on-the-fly during minimally invasive surgery.
- Requirements
  - Surgeons: sterilizable; not changing standard operation procedure; enabling Augmented Reality (considering quality and quantity of acquired data for registration purposes with preoperatively acquired data)
  - Endoscope manufacturers: cheap (!); based on available standard endoscope technology; must be easily integrated into current endoscope systems

Idea of MUSTOF

Parallel acquisition with ToF camera and CCD camera

Parallel acquisition of depth and image data combining a ToF and a CCD chip:
Multi-Sensor-Time-Of-Flight (MUSTOF) endoscope

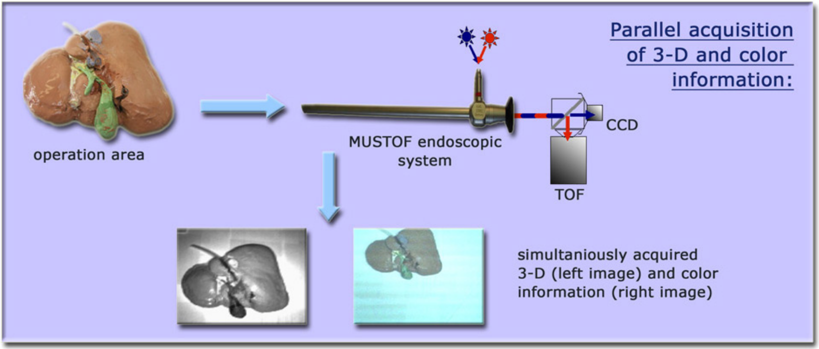


Figure: Paketantrag 'Towards NOTES^{3D}'

Required Methods

Essential algorithms for MUSTOF technology:

- Calibration of ToF camera and CCD camera
- Registration of ToF data and CCD data
- Feature extraction and detection
- Reconstruction of static or almost static 3-D scenes
- Image processing and filtering for higher quality

Required Methods

Calibration and Registration of ToF camera and CCD camera

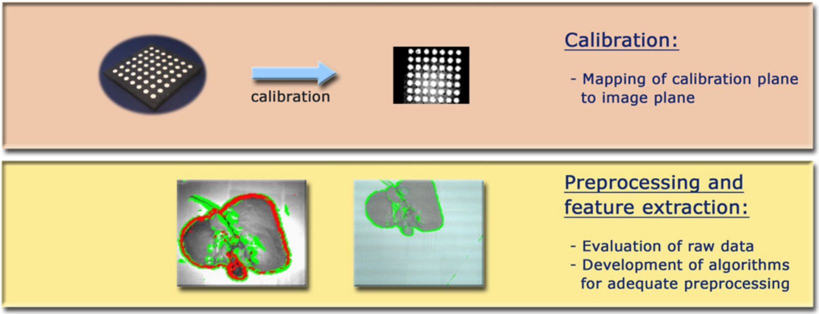


Figure: Paketantrag 'Towards NOTES^{3D}'

Required Methods

Reconstruction of static or almost static 3-D scenes

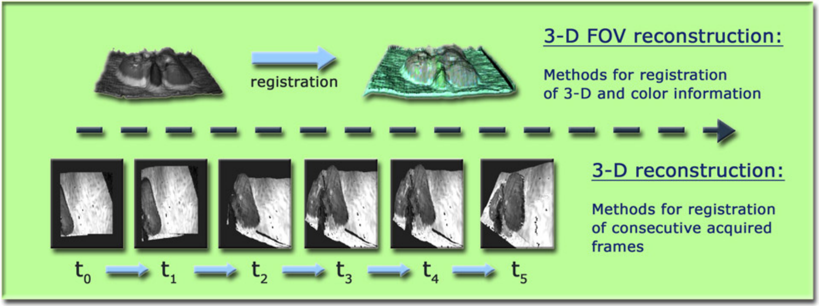


Figure: Paketantrag 'Towards NOTES^{3D}'

Navigation support - Orientation

Finding the entry point to the peritoneal cavity

Challenge:

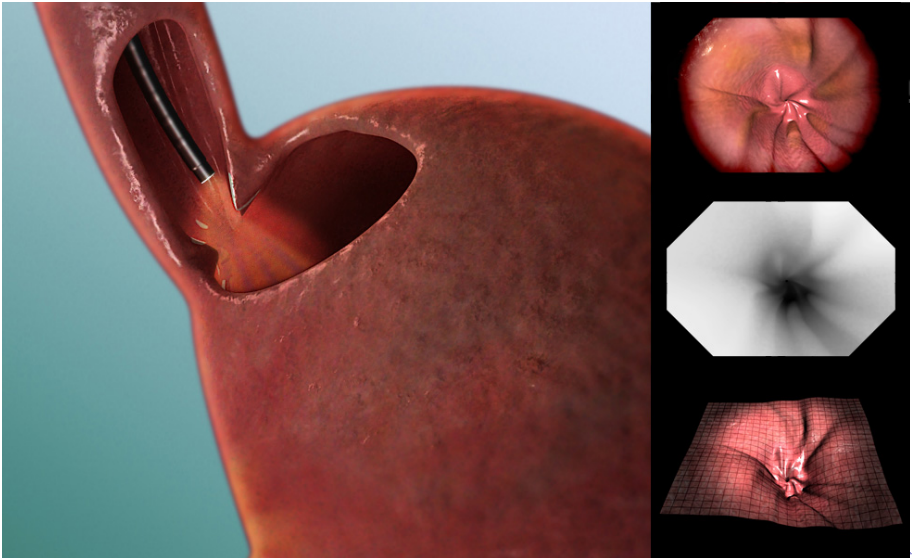
- More information on position and orientation of the robotic device or the endoscope

Solution:

- Nonrigid registration of intraoperative 3-D data with preoperative CT or MR data is possible
- Calculated transformation parameters can be used to represent, correct und visualize actual position and orientation

Navigation support - Orientation

Finding the entry point to the peritoneal cavity



Navigation support - Augmented Reality

Finding the entry point to the peritoneal cavity

Challenge:

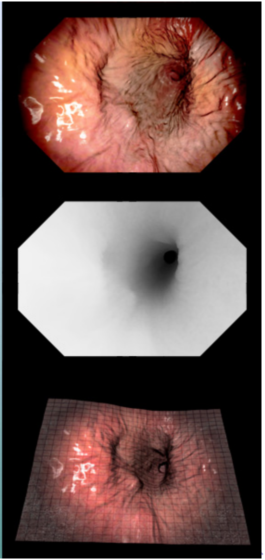
- Avoid injuries of hidden organs and vessels, e.g. while finding the entry point to the peritoneal cavity
- Knowledge of structures behind the visible wall is needed for a safe incision

Solution:

- Registration with preoperative volumes
- Segmentation of objects of interest in the preoperative volumes
- Adaption of those objects by iteratively computed transformation parameters
- Visualization of hidden organs or vessels in intraoperative endoscopic images by augmented reality

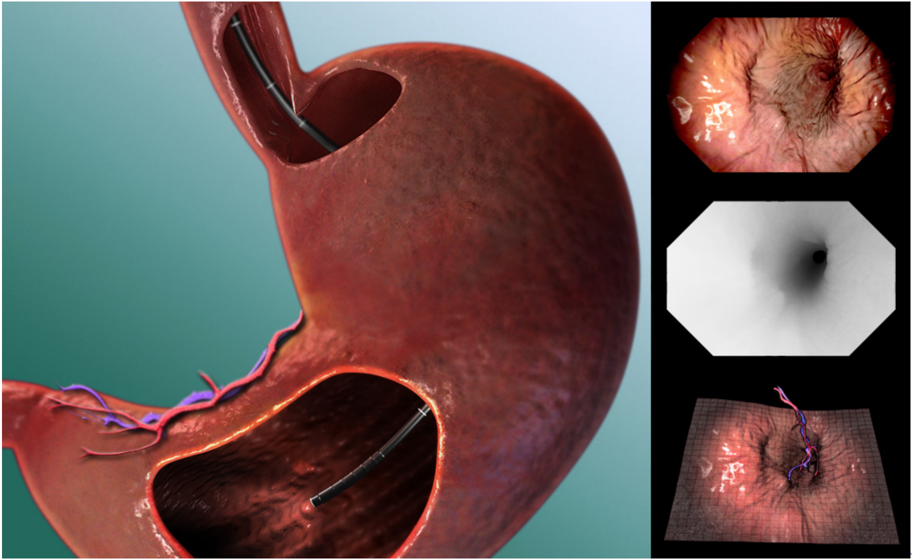
Navigation support - Augmented Reality

Finding the entry point to the peritoneal cavity



Navigation support - Augmented Reality

Finding the entry point to the peritoneal cavity



Navigation support - Off-axis view

Finding the entry point to the peritoneal cavity

Challenge:

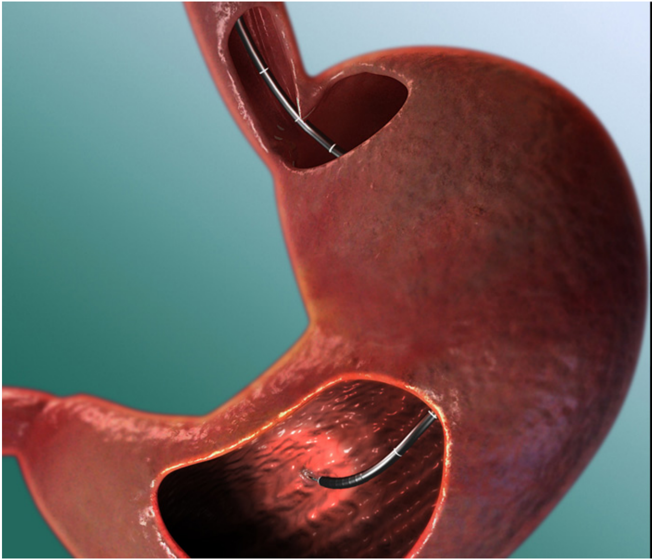
- Overcome boundaries of limited field of view like axis in-line view and loss of spatial orientation

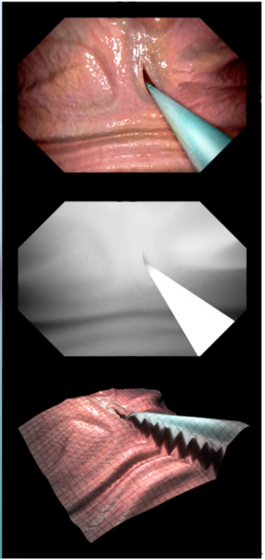
Solution:

- 3-D surface knowledge can be used to extend and virtually rotate the field of view
- With a 3-D mosaicking technique, the field of view can be extended by reconstruction of the operation area.

Navigation support - Off-axis view

Finding the entry point to the peritoneal cavity





Navigation support - Collision prevention

Finding the entry point to the peritoneal cavity

Challenge:

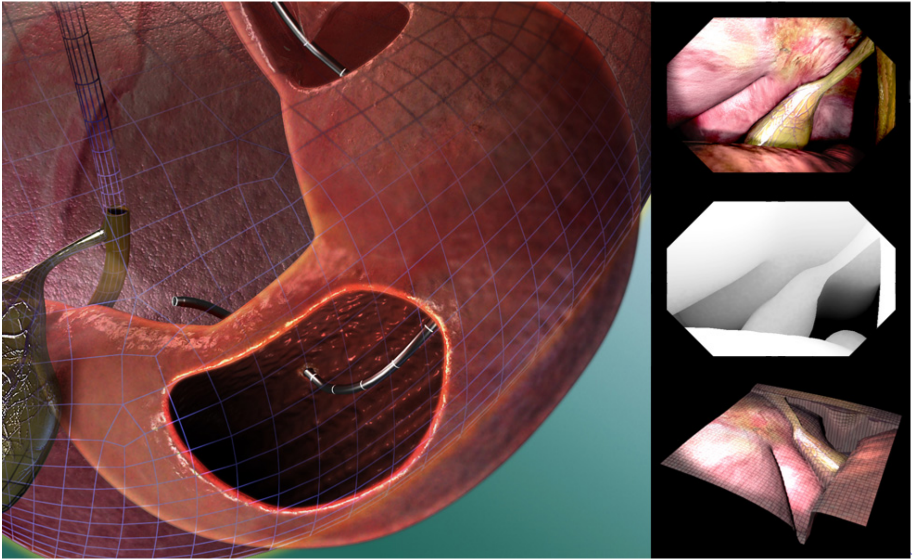
- Provide a higher grade of safety for automatic tools and robotic devices
- Especially important with multiple instruments through only one flexible endoscope

Solution:

- With real-time distance information efficient collision prevention with tissue or other instruments can be enabled
- Auto-positioning depending on respiration or other patient movements will be very helpful.

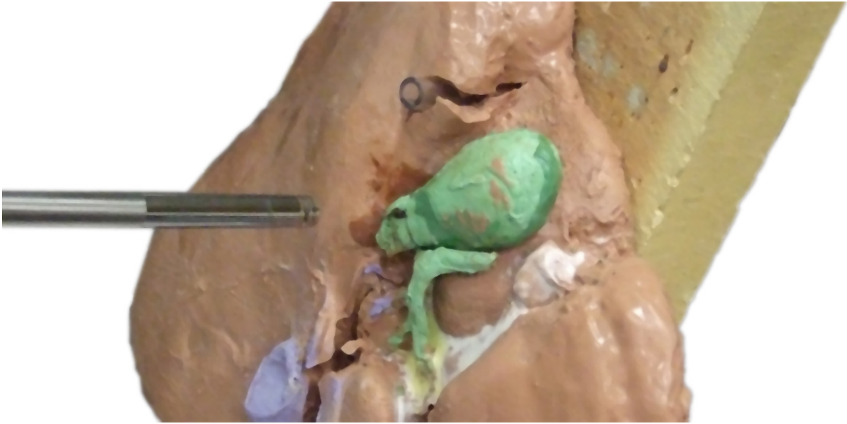
Navigation support - Collision prevention

Finding the entry point to the peritoneal cavity



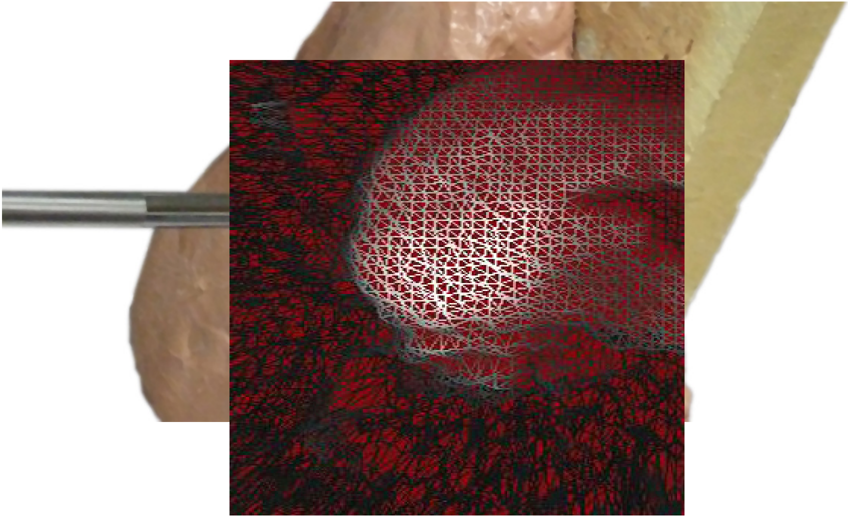
Preliminary results

Liver phantom with gall bladder



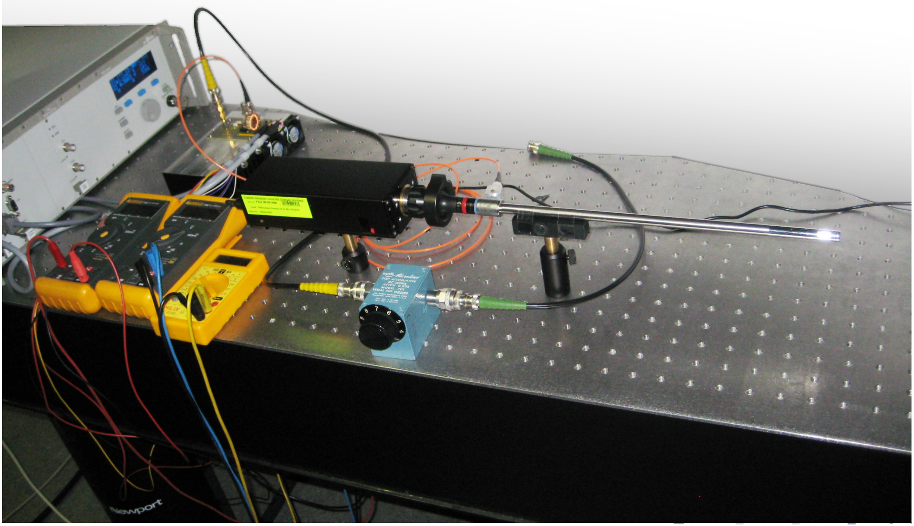
Preliminary results

Liver phantom with gall bladder



Preliminary results

Stomach with cubes inside



Preliminary results

Stomach with cubes inside

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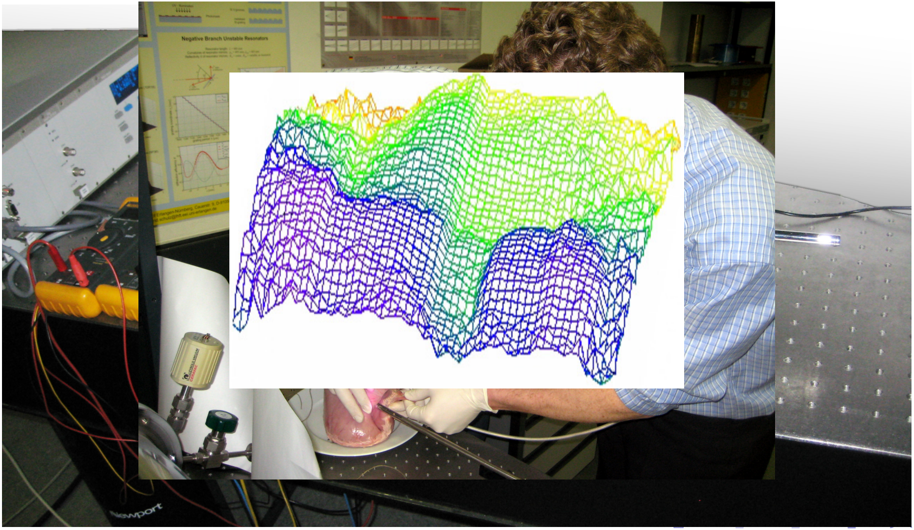
Stomach with cubes inside



Preliminary results

Stomach with cubes inside

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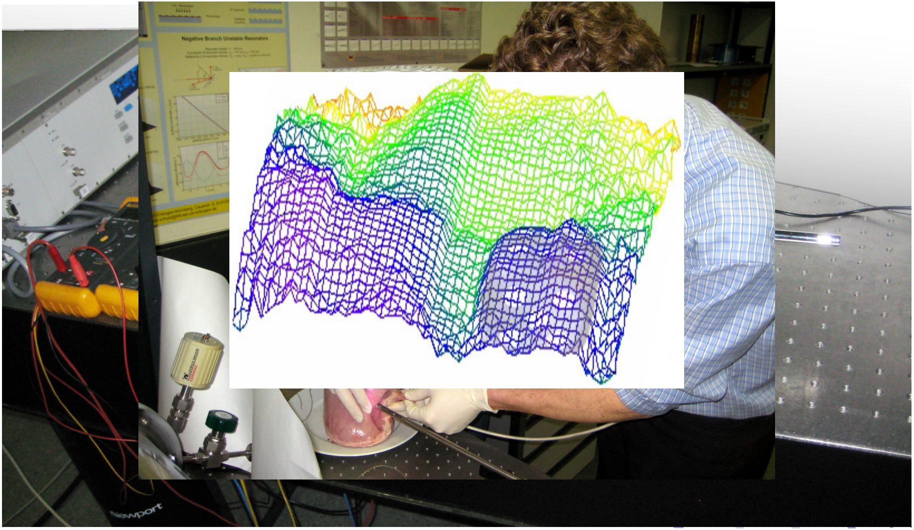
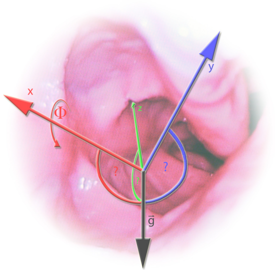
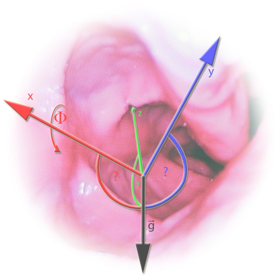
Stomach with cubes inside



Overview



Overview

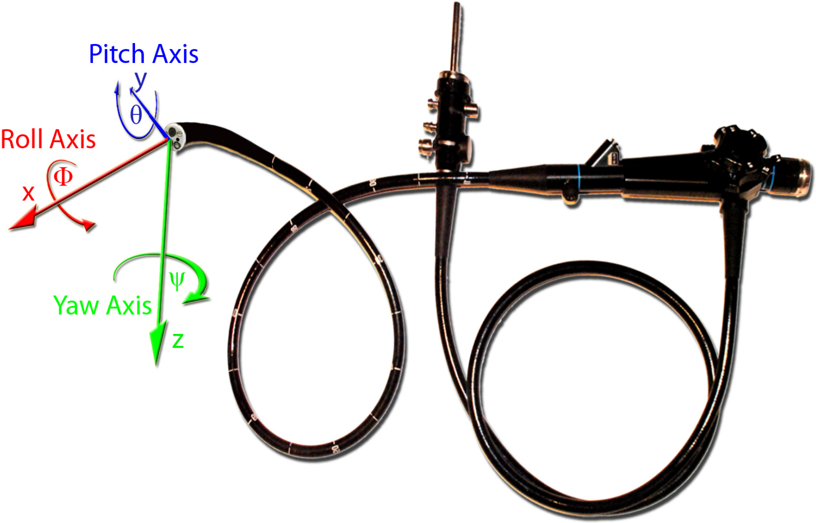


Problem of unknown image orientation

with flexible endoscopy

Roll Pitch Yaw description

for endoscopic orientation

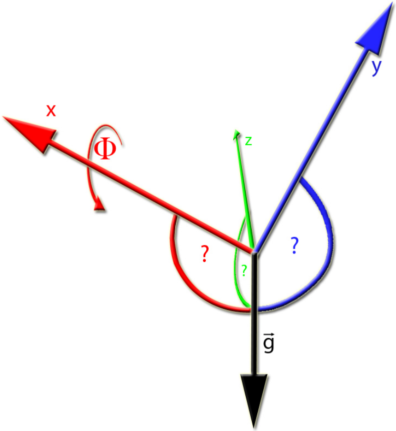


Orientation of endoscope tip

Roll Calculation

How can roll Φ (= orientation of endoscope tip) be calculated out of measured forces on the axes x, y, z and the vector $\vec{g}$ without any further angle information?

$\Rightarrow$ $\vec{x}$, $\vec{y}$ and $\vec{z}$ are orthogonal axes of the Cartesian "board navigation system"



Roll Pitch Yaw (DIN 9300 aeronautical standard)

Measurement of gravity

How have rotation parameters Φ, Θ and Ψ of the IMU (Inertial Measurement Unit) to be chosen to get back to a spatial orientation with $\vec{z} \parallel \vec{g}$?

$$\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\Phi) & \sin(\Phi) \\ 0 & -\sin(\Phi) & \cos(\Phi) \end{pmatrix} \cdot \begin{pmatrix} \cos(\Theta) & 0 & -\sin(\Theta) \\ 0 & 1 & 0 \\ \sin(\Theta) & 0 & \cos(\Theta) \end{pmatrix} \cdot \cdot \begin{pmatrix} \cos(\Psi) & \sin(\Psi) & 0 \\ -\sin(\Psi) & \cos(\Psi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} = \begin{pmatrix} -\sin(\Theta)g \\ \sin(\Phi)\cos(\Theta)g \\ \cos(\Phi)\cos(\Theta)g \end{pmatrix} \quad (1)$$

with Φ: Roll, Θ: Pitch, Ψ: Yaw
and $F_{x,y,z}$: measured acceleration, g: gravity

Roll computation

Measurement of gravity

Using the two-argument function atan2 to handle the ambiguity of the arc tangent in a range of $\pm\pi$ one finally can compute **roll** Φ for $F_x \neq \pm g$ and **pitch** Θ for all values:

$$\frac{F_y}{F_z} = \frac{\sin(\Phi)\cos(\Theta)}{\cos(\Phi)\cos(\Theta)} \quad \Rightarrow \quad \Phi = atan2(F_y, F_z) \tag{2}$$

$$F_x = -\sin(\Theta) \cdot g \quad \Rightarrow \quad \Theta = \arcsin\left(\frac{-F_x}{g}\right) \tag{3}$$

Limitations

Measurement of gravity

Orientation computation is limited:

- $\vec{g}$ determines just two degrees of freedom
  $\Rightarrow$ **yaw Ψ cannot be computed** at any time
- singularity occurs at $F_x = \pm g$ ($\Theta = \pm\pi \rightarrow F_y = F_z = 0$)
  $\Rightarrow$ roll Φ can not be computed when the endoscope **points downward**
- no calculation during **high superposed acceleration** ΔF_{absmax}
  $\Rightarrow$ angle is freezed untill $\Delta F < \Delta F_{absmax}$ is reached again

$$|\sqrt{F_x^2 + F_y^2 + F_z^2} - g| < \Delta F_{absmax} \qquad (4)$$

Endorientation algorithm

Block diagram

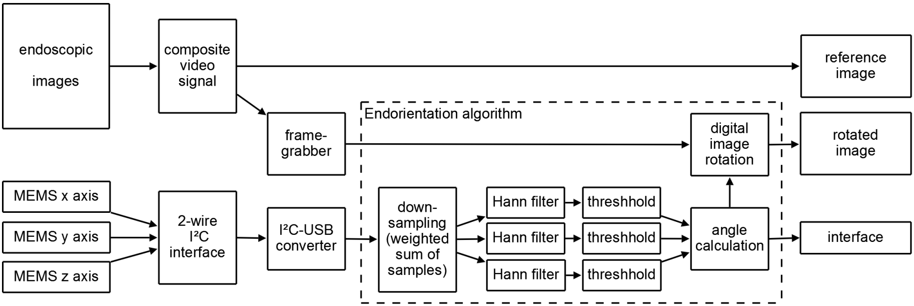


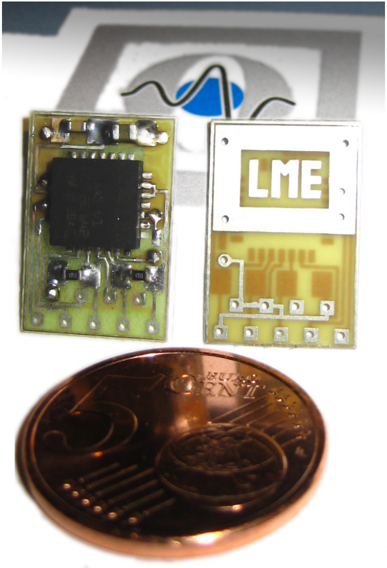
Figure: Principle of Endorientation algorithm

First Prototype

Solution for loss of spatial orientation

Circuit board with MEMS chip STM AIS326DQ for acceleration measurement, 10uF/100nF SMD capacitors for power supply HF denoising and 4k7 SMD resistors for I^2C adaption

- 3-axis MEMS accelerometer
- 0804 capacitors
- range ± 6g
- overall size 12x18mm
- communication via two-wire I^2C interface

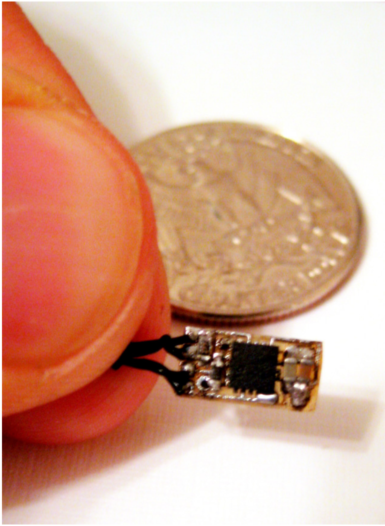


New smaller Prototype

Solution for loss of spatial orientation

Circuit board with MEMS chip STM LIS331DL for acceleration measurement, 10uF/100nF SMD capacitors for power supply HF denoising and 4k7 SMD resistors for I^2C adaption

- 3-axis MEMS accelerometer
- 0603 capacitors
- range $\pm 2.3g$
- overall size 5x8mm
- communication via two-wire I^2C interface

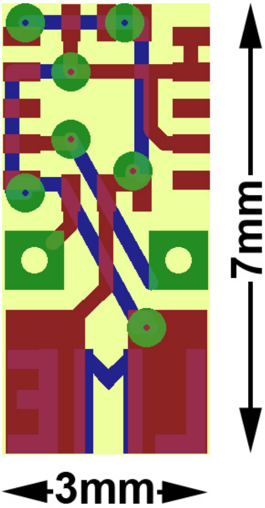


Upcoming Design

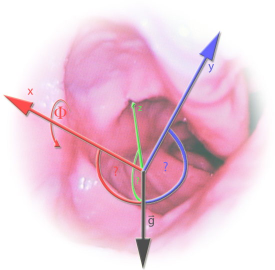
3mm outer diameter for the use in a endoscopic working channel

Circuit board with MEMS chip STM LIS331DL for acceleration measurement and 10uF/100nF SMD capacitors for power supply HF denoising

- 3-axis MEMS accelerometer
- 0402 capacitors
- range ± 2.3g
- overall size 3x7mm
- communication via two-wire I^2C interface

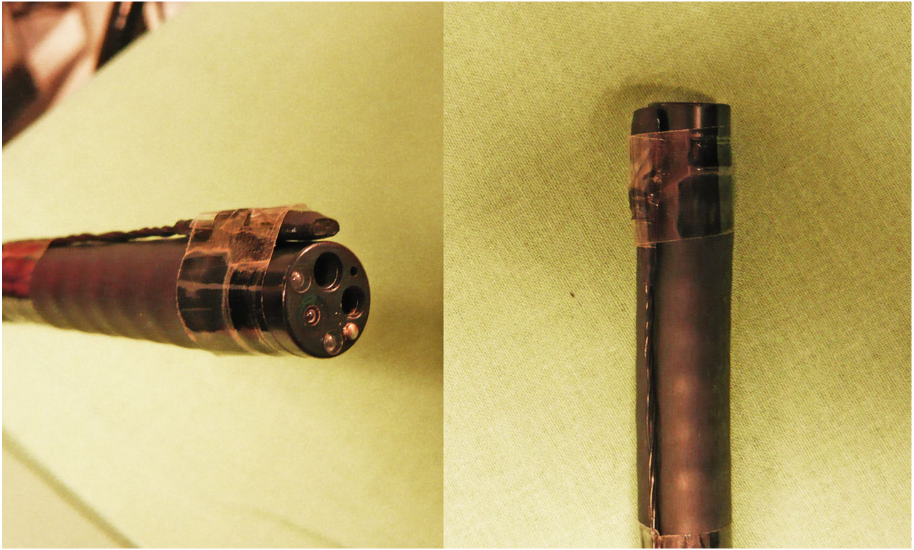


Overview



Evaluation prototype

external sensor on endoscope’s tip



Evaluation prototype

external sensor on endoscope's tip

First results

Software solution

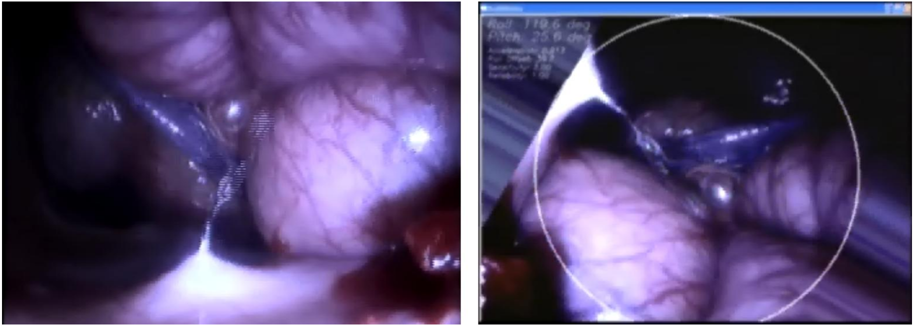
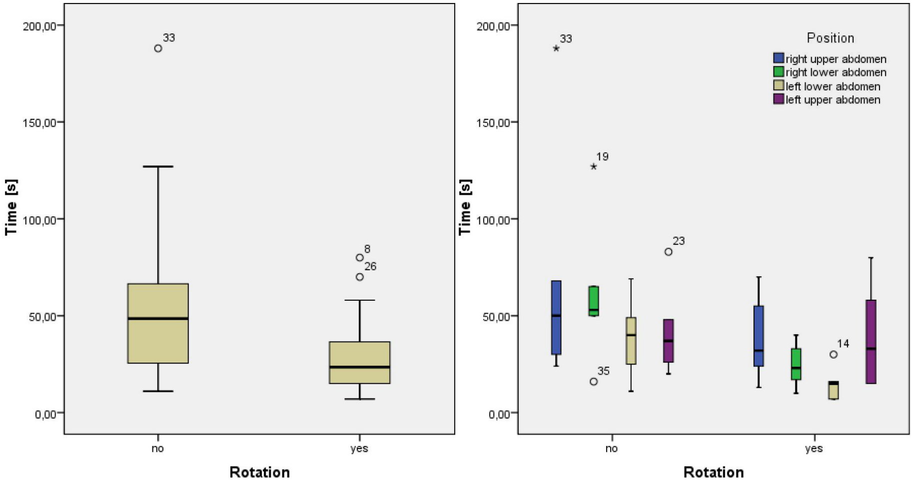


Figure: Original (l) and rectified (r) image

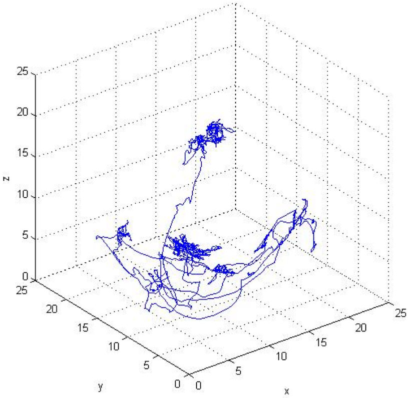
Clinical Evaluation

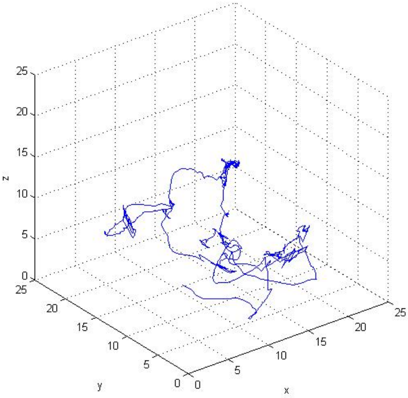
Average time comparison without and with image rectification



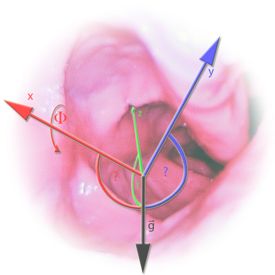
Clinical Evaluation

Original vs. rectified images: total path length of 650 vs. 317 inches





Overview



Summarize

Applications and Challenges

Supporting problems of NOTES will be THE application for endoscopic 3-D systems:

- Access to peritoneal cavity
  - Registering online optic 3-D data with preoperative MR or CT visualized by Augmented Reality
- Maintaining spatial orientation, distance values or other 3-D data
  - collision prevention, motion compensation and automatic positioning of surgery tools
  - reconstruction of static scenes (3-D mosaicking)

Advantages of our MUSTOF technology:

- real-time 3-D information
- hardware with short innovation cycles (ToF-chip)
- real 3-D measurements (not only 3-D impression)

Conclusion

Endoscopic 3-D information (e.g. by MUSTOF) are precondition to

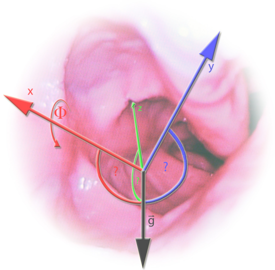
- calculate intra-operative orientation
  $\Rightarrow$ registrating with pre-operative MR/CT volumes
- avoid injuries of hidden organs and vessels
  $\Rightarrow$ making them visible by augmented reality
- provide an enhanced field of view
  $\Rightarrow$ computing off-axis view or reconstructed area by stitching
- to enable collision prevention, motion compensation and automatic positioning of surgery tools
  $\Rightarrow$ using a real-time distance measurement

Conclusion

Contributions of an Enhanced Endoscopic Engineering (e.g Endorientation):

- Idea:
  $\Rightarrow$ tiny chip can be fixed even on a flexible endoscope's tip
  $\Rightarrow$ orientation of endoscopic view is rectified
  $\Rightarrow$ a stable horizon is provided
- Solution:
  $\Rightarrow$ tiny circuit board, I2C communication and register setting
  $\Rightarrow$ down sampling, filtering and threshholding
  $\Rightarrow$ image rotation and rectification
- Evaluation:
  $\Rightarrow$ interventions easier for surgeons
  $\Rightarrow$ better video hardware needed

Overview



Outlook

Next steps:

- Use new ToF camera with higher resolution (41.000 pixels instead of 3.000 pixels)
- Design rotation correction sensor even smaller (3×6mm)
- Evaluation of accuracy and benefit of both approaches
- Publishing results

The End

- Thank you for your attention!
- **Endorientation Demo**
- Any further questions?