Spatial orientation
in Natural Orifice Translumenal Endoscopic Surgery

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Content

1. Introduction/Motivation
   - Idea of NOTES
   - NOTES routes and procedures
   - NOTES instruments
   - Challenges with NOTES

2. NOTES
   - Idea of MUSTOF

3. Time-of-Flight (ToF) Endoscopy
   - Time-of-Flight (ToF) principle
   - Idea of MUSTOF

4. Biomedical IMU applications
   - Endoscopic image orientation
   - Evaluation

5. Summarize

6. Outlook

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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
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

2-nd Russian-Bavarian Conference
on
Bio-Medical Engineering
June 14/15, 2006, Moscow

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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\textsuperscript{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

3\textsuperscript{rd} Russian-Bavarian Conference on Bio-Medical Engineering
July 2/3, 2007, Erlangen

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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

2000, Seifert, Wehrmann...Caspary, F.a.M.
endoskopische transgastr. Nekrosektomie

2002, Rao & Reddy, India, Henoscopy, Transgastric Appendectomy

2004, Rao & Reddy, India, Human Transgastric Appendectomy

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)
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
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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

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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)
Some more actual discussed and tried therapies with NOTES:

- splenectomy (2006)
- nephrectomy
- hernia repair
- heptectomy
- 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

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Access: Keeping the bowel loops apart using fluid

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

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Access: Encircling 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
Closure of gastric or colonic wall incision (MITI)

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Endoclips, H. Feussner 2006
Closure of gastric or colonic wall incision (MITI)
dissolving magnesium spike, H. Feussner 2006
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Closure of gastric or colonic wall incision (MITI)
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Stapling devices

Figure: Kaehler: Endoscopic stapler
Suturing devices

Figure: Olympus 'Eagle Claw'
Suturing devices

Figure: USGI Medical: G-Prox
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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
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 ⇒ item we can support
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- Management of intraperitoneal complications and hemorrhage
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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
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\textsuperscript{3D}',

Collision handling with NOTES

Collision detection

Collision handling of the optics

Instrument detection

Collision handling with telemanipulator

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Dynamic reconstruction

Paketantrag 'Towards NOTES\textsuperscript{3D},'

- Registration of subnets
- Detection of dynamic areas
- Detection of integrated instruments
- Interactive 3-D reconstruction

Input data using MUSTOF technology
Development of a multitasking platform
As it could look like

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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 μm × 40 μm
- Modulation frequency: 20 – 30 MHz (⇒ λ = 15 – 10 m)
- Frame rate: >15 fps

Figure: ToF-camera and example images
State of the Art
Time-of-Flight (ToF) technology

- Lateral resolution: $176 \times 144$ pixel
- Depth resolution: $2.5$ mm
- Wavelength: $870$ nm
- Pixel dimension: $40 \mu m \times 40 \mu m$
- Modulation frequency: $20 MHz \ (\Rightarrow \lambda = 15 m)$
- Frame rate: $>25$ fps

Figure: ToF-camera and example images
March 1\textsuperscript{st}, 2009: PMDvision Cam Cube

Time-of-Flight (ToF) technology

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

\textbf{Figure:} ToF-camera and example images
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Time-of-flight principle

Pulsed modulation
Time-of-flight principle
Continuous wave modulation

IR

PMD

TOF

distance
"Ladungsschaukel"

charging swing

\[ -g_k(t + \tau_{k+2}) \quad \text{S}_d(t) \quad g_k(t + \tau_k) \]

\[ C_k(\tau_k) \]
ToF accuracy

Illumination requirements

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

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

- \(c\): relative speed of light
- \(f_{\text{mod}}\): modulation frequency
- \(P_{\text{laser}}\): power of modulated signal
- \(P_{\text{amb}}\): ambient light power
- \(A\): illuminated area
- \(k_{\text{opt}}\): optical system constant
- \(q_e\): quantum efficiency
- \(r\): target reflectivity
- \(T\): integration time

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**ToF accuracy**

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ToF accuracy

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- $r$: target reflectivity
- $T$: integration time
Laser diode modulation
nonlinear characteristics

- fast modulation up to 500MHz
- high power
- differential resistance
- threshold current between spontaneous and stimulated emission
- linear mode in the range of $I_{\text{min}}$ to $I_{\text{max}}$
Illumination with Laser Diode and Bias-Tee

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

\[ U \]
\[ +U_{\text{puls}} \]
\[ -U_{\text{puls}} \]

\[ I_{\text{bias}} \]

\[ I_{\text{bias}} \]

\[ I_{\text{puls}} \]

\[ I_{\text{LD}} \]

\[ \Delta R_{LD} \]

\[ LD \]

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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

**Calibration:**
- Mapping of calibration plane to image plane

**Preprocessing and feature extraction:**
- Evaluation of raw data
- Development of algorithms for adequate preprocessing

*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 and visualize actual position and orientation

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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

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Navigation support - Augmented Reality
Finding the entry point to the peritoneal cavity

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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

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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
Preliminary results

Stomach with cubes inside
Preliminary results

Stomach with cubes inside
Preliminary results

Stomach with cubes inside
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Problem of unknown image orientation with flexible endoscopy
Roll Pitch Yaw description
for endoscopic orientation
How can roll $\Phi$ (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 $\Phi$, $\Theta$ and $\Psi$ of the IMU (Inertial Measurement Unit) to be chosen to get back to a spatial orientation with $\vec{z} \parallel \vec{g}$?

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

(1)

with $\Phi$: Roll, $\Theta$: Pitch, $\Psi$: Yaw
and $F_{x,y,z}$: measured acceleration, $g$: gravity
Roll computation
Measurement of gravity

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

$$\frac{F_y}{F_z} = \frac{\sin(\Phi) \cos(\Theta)}{\cos(\Phi) \cos(\Theta)} \Rightarrow \Phi = \text{atan2}(F_y, F_z)$$  \hspace{1cm} (2)

$$F_x = -\sin(\Theta) \cdot g \Rightarrow \Theta = \arcsin \left( \frac{-F_x}{g} \right)$$  \hspace{1cm} (3)
Limitations
Measurement of gravity

Orientation computation is limited:

- $\mathbf{g}$ determines just two degrees of freedom
  $\Rightarrow$ yaw $\Psi$ cannot be computed at any time

- singularity occurs at $F_x = \pm g$ ($\Theta = \pm \pi \Rightarrow F_y = F_z = 0$)
  $\Rightarrow$ roll $\Phi$ can not be computed when the endoscope points downward

- no calculation during high superposed acceleration $\Delta F_{absmax}$
  $\Rightarrow$ angle is freezed untill $\Delta F < \Delta F_{absmax}$ is reached again

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

Block diagram

endoscopic images

composite video signal

frame-grabber

2-wire I²C interface

I²C-USB converter

down-sampling (weighted sum of samples)

Hann filter

Hann filter

Hann filter

Hann filter

threshold

threshold

threshold

angle calculation

digital image rotation

reference image

rotated image

interface

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, 10μF/100nF SMD capacitors for power supply HF denoising and 4k7 SMD resistors for I^2C adaption

- 3-axis MEMS accelerometer
- 0603 capacitors
- range ±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 I²C interface
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5. Outlook

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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

![Box plots showing time comparison between rotation with and without image rectification.](image)
Clinical Evaluation

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

1. Introduction/Motivation
2. NOTES
   - Idea of NOTES
   - NOTES routes and procedures
   - NOTES instruments
   - Challenges with NOTES
3. Time-of-Flight (ToF) Endoscopy
   - Time-of-Flight (ToF) principle
   - Idea of MUSTOF
4. Biomedical IMU applications
   - Endoscopic image orientation
   - Evaluation
5. Summarize
6. Outlook
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 ⇒ registrating with pre-operative MR/CT volumes
- avoid injuries of hidden organs and vessels ⇒ making them visible by augmented reality
- provide an enhanced field of view ⇒ computing off-axis view or reconstructed area by stitching
- to enable collision prevention, motion compensation and automatic positioning of surgery tools ⇒ using a real-time distance measurement

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Conclusion

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

- **Idea:**
  - tiny chip can be fixed even on a flexible endoscope’s tip
  - orientation of endoscopic view is rectified
  - a stable horizon is provided

- **Solution:**
  - tiny circuit board, I2C communication and register setting
  - down sampling, filtering and threshholding
  - image rotation and rectification

- **Evaluation:**
  - interventions easier for surgeons
  - better video hardware needed
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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?