Time-of-Flight Based Endoscopy for NOTES Interventions: Challenges and Limitations

July 4, 2008

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Introduction

Time-of-Flight (ToF) technology

Technical specifications

- Framerate: 12...50 fps
- Lateral resolution: 16×64 pixel ... 144×171 pixel
- Depth resolution: dependent on measured depth
- Active illumination of the scene with eye-safe infrared LEDs
- Output: 3-D coordinates (describing the 3-D surface of the current field of view), gray value image (encoding the amount of reflected signal \( \rightarrow \) gray value depends on reflectivity of material and distance)

\[
\tau_d = \frac{2 \cdot R}{c}
\]

Figure: ToF camera MESA Imaging GmbH; middle: ToF principle (\( R \), distance, \( c \), speed of light, \( \tau_d \), travel time of impulse \( P_{opt} \)); right: reconstruction of human hand

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Core idea: transferring the Time-of-Flight (ToF) distance measurement principle to a rigid endoscope optic

**Figure:** Scheme of the Multisensor-Time-of-Flight (MUSTOF) endoscope. Red: ToF optical reference signal; green: standard illumination source.
Introduction

Clinical relevance

Standard visualization

- endoscopes acquire 2D distorted images
- endoscope use front illumination unit \(\Rightarrow\) huge contrast, no shadows, flat appearance \(\Rightarrow\) lack of depth perception

is significant sensory loss for surgeon

Benefit of additional real-time 3D information for NOTES interventions

- increased efficiency and spatial control
- enables Augmented Reality
- registration with pre-operative data
MUSTOF endoscopy
Determining the physical boundaries

- ToF sensors are typically operating at 870 nm → The ToF sensors itself as well as the endoscope optic provide more variability (see figures below)
- Benefit: additional modification of lense system is not necessary

**Figure:** Transmission properties of endoscope optic.

**Figure:** Sensitivity of a ToF sensor element.

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For ToF cameras building a proper illumination unit is as complex as building the ToF sensor.

What optical power do we need to illuminate the operation area? What measurement uncertainty do we want to achieve?

Measurement uncertainty: 1 mm has to be achieved reliably; otherwise clinical relevance is not ensured.

| Table: Specification of the ToF camera PMD[vision]3k-S. |
|---------------------------------|------------------|
| Pixel dimensions                | 100µm × 100µm    |
| Lateral Resolution             | 64×48 pixel      |
| Illumination Power             | ≈ 3W             |
| Wavelength                     | 870 nm           |
| Modulation Frequency           | 10-30 MHz        |
| Receiver Optics                | C-Mount          |
Standard deviation $\sigma$ of range error can be computed using modulation frequency $f$, speed of light $c$, number $M$ of photoelectrons generated by modulated light source and number $B$ of photoelectrons generated by background light:

$$\sigma = \frac{c}{2\sqrt{8f}} \cdot \frac{1}{M} \cdot \sqrt{B + \frac{M}{2}}$$

Using $f = 100\ MHz$ and $M = 100000$ the following values are obtained for varying $B$ (Figure: next slide)
Observation 1: Assuming $M=100000$ photoelectrons generated by 100 MHz-modulated light source in each pixel a distance resolution of 1 mm is achievable.

Observation 2: The influence of background illumination is not too severe; for minimally invasive interventions additional light sources are controllable or neglectible.

Question: Can we generate $M=100000$ photoelectrons? And what optical power is needed?

**Figure:** Standard deviation of range measurement error in mm with respect to background illumination.
The optical power $P$ required to generate $N_e$ photoelectrons is determined by

$$P = \frac{N_e \cdot \frac{A_S}{A_P} \cdot h \cdot c}{\phi \cdot (\frac{D}{2R})^2 \cdot k \cdot q(\lambda) \cdot \lambda \cdot T}$$ (2)

with $A_S$: area of ToF sensor, $A_P$: area of pixel, $h$: Planck’s constant, $c$: speed of light, $\phi$: remission of object, $D$: aperture of lens, $R$: distance of object, $k$: attenuation, $q(\lambda)$: quantum efficiency, $\lambda$: wavelength of light, $T$: integration time

Specific (moderate) values: $\phi=0.8$, $k=0.3$, $\lambda=850$ nm, $q(\lambda)=0.9$, $T=10$ ms

The term $(\frac{D}{2R})$ assumes that the observed object is a Lambert reflector and was validated for scenes with observable distances in the range of meters; both might not be true for endoscopic ToF data acquisition (closeness to scene as well as Lambertian properties).
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Optical power for 1 mm measurement uncertainty (cont.)

Figure: Illustration of optical transmission channel and loss of optical power.

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Optical power for 1 mm measurement uncertainty (cont.)

Figure: Required optical power of illumination source with respect to $D/(2R)$
Figure: Required optical power of illumination source with respect to $\frac{D}{2R}$ in the range of 0.8...1.0
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Remarks concerning the validity of the previous considerations

Why are the drawn conclusion too optimistic?
1. Thermal noise, reset noise, quantization noise are not reflected in the equations.
2. Secondary reflections are not considered.

Why are the drawn conclusions too pessimistic?
1. The MUSTOF endoscope provides a point-light source in contrast to the LED array of standard ToF cameras.
2. Using laser LEDs with appropriate drivers enables the generation of a more accurately modulated signal.

And now?
- The equations point out significant aspects of the transmission chain which have to be considered for building an endoscope which is feasible in minimally invasive surgery.
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Preliminary results

Observing a card with printed numbers.

Figure: Observed card.

Figure: Card observed with PMD3kS.

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Table: 3D Measurement uncertainty in mm with respect to certain preprocessing steps and/or averaging applied to distance data before computing 3D reconstruction.
MUSTOF endoscopy
Preliminary results

Observing a card with printed numbers.

Figure: Observed card.

Figure: Card observed with PMD19k.

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MUSTOF endoscopy

Preliminary results

Observing a liver model. (Observed part marked black.)

Figure: Observed liver model.  
Figure: Card observed with PMD19k.

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MUSTOF endoscopy
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Finally, MUSTOF endoscopy is a completely new medical modality. To make it feasible for NOTES interventions the following tasks have to be fulfilled:

1. The necessary signal requirements (illumination power, modulation requirements) have to be met.
2. A stable measurement uncertainty of 1 mm has to be reached.
3. Lens distortions have to be corrected to achieve absolute correctness of 3D reconstruction.
Thank you for your attention. Questions?