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

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Chair of Pattern Recognition (Informatik 5)

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Content

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 $\Longrightarrow$ gray value depends on reflectivity of material and distance)

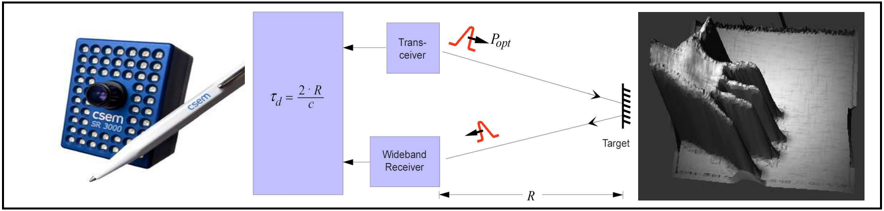

Figure: ToF camera MESA Imaging GmbH; middle: ToF principle (R..distance, c..speed of light, τ_d..travel time of impulse P_{opt}); right: reconstruction of human hand

Introduction (cont.)

Multisensor-Time-of-Flight-Endoscopy (MUSTOF-Endoscopy)

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

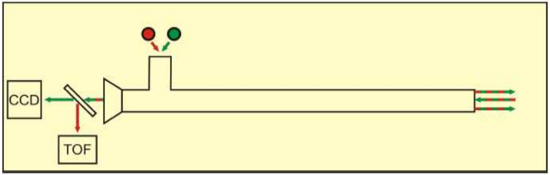

Figure: Scheme of the Multisensor-Time-of-Flight (MUSTOF) endoscope. Red: ToF optical reference signal; green: standard illumination source.

Introduction

Clinical relevance

Standard visualization

- endoscopes acquire 2D distorted images
- endoscope use front illumination unit $\Longrightarrow$ huge contrast, no shadows, flat appearance $\Longrightarrow$ 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

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Determining the physical boundaries

- ToF sensors are typically operating at 870 nm $\Longrightarrow$ 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

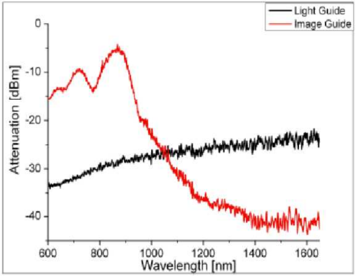

Figure: Transmission properties of endoscope optic.

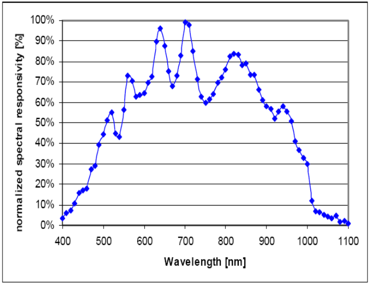

Figure: Sensitivity of a ToF sensor element.

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Illumination unit

- 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.

Pixel dimensions	$100\mu m \times 100\mu m$
Lateral Resolution	64×48 pixel
Illumination Power	$\approx$ 3W
Wavelength	870 nm
Modulation Frequency	10-30 MHz
Receiver Optics	C-Mount

Table: Specification of the ToF camera PMD[vision]3k-S.

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Standard deviation of range measurement error

- Standard deviation σ 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:

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

- Using $f = 100\ MHz$ and $M = 100000$ the following values are obtained for varying B (Figure: next slide)

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Standard deviation of range measurement error (cont.)

- 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?

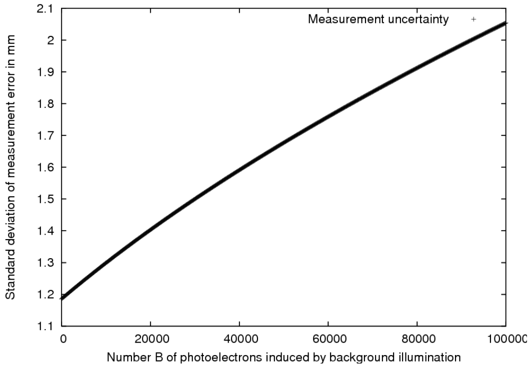

Figure: Standard deviation of range measurement error in mm with respect to background illumination

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Optical power for 1 mm measurement uncertainty

- The optical power P required to generate N_e photoelectrons is determined by

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

  with A_S: area of ToF sensor, A_P: area of pixel, h: Planck's constant, c: speed of light, ϕ: remission of object, D: aperture of lens, R: distance of object, k: attenuation, $q(\lambda)$: quantum efficiency, λ: wavelength of light, T: integration time
- Specific (moderate) values: ϕ=0.8, k=0.3, λ=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.)

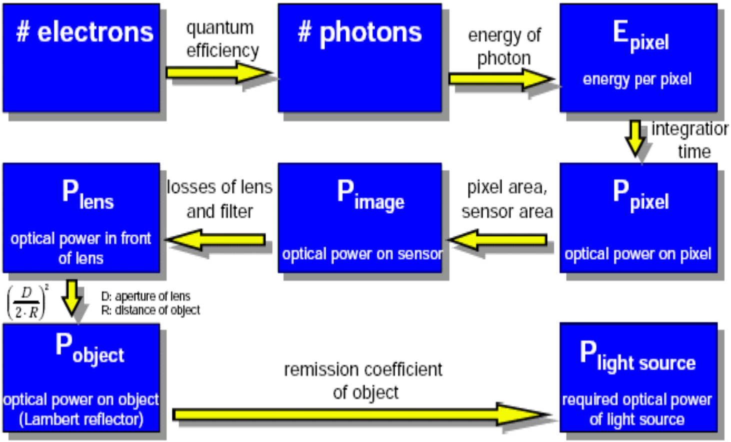

Figure: Illustration of optical transmission channel and loss of optical power.

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Optical power for 1 mm measurement uncertainty (cont.)

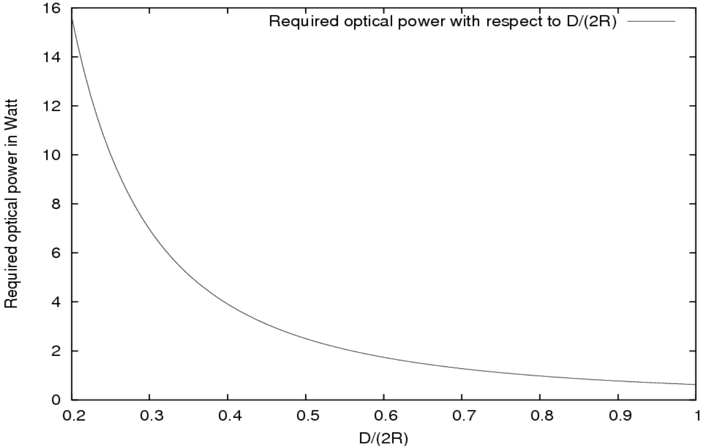

Figure: Required optical power of illumination source with respect to $\frac{D}{2R}$

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Optical power for 1 mm measurement uncertainty (cont.)

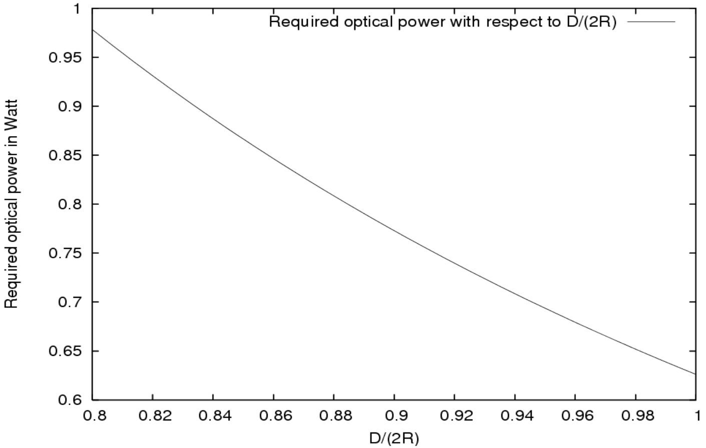

Figure: Required optical power of illumination source with respect to $\frac{D}{2R}$ in the range of 0.8...1.0

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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.

MUSTOF endoscopy

Preliminary results

Observing a card with printed numbers.

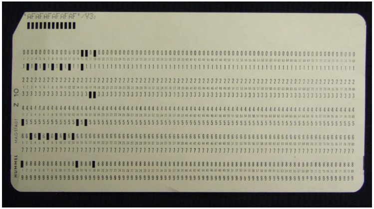

Figure: Observed card.

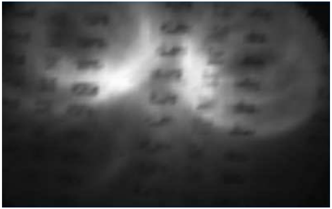

Figure: Card observed with PMD3kS.

n=	1	10	20	50
none	10.9	5.5	4.0	2.9
gauss	7.5	4.7	3.6	2.8
median(3x3)	6.9	8.1	7.4	3.9
median(5x5)	7.1	6.2	5.2	2.7

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

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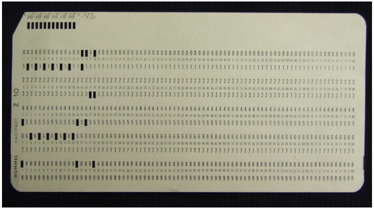

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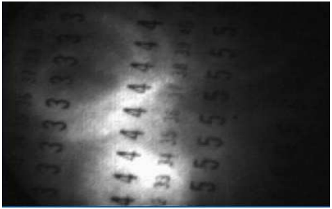

Figure: Card observed with PMD19k.

n=	1	10	20	50
none	53.9	17.5	12.3	5.8
gauss	21.3	6.9	4.9	2.4
median(3x3)	27.1	8.5	6.2	3.4
median(5x5)	19.9	6.7	4.7	2.7

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 liver model. (Observed part marked black.)

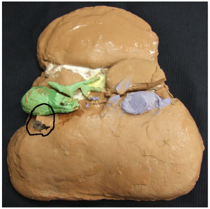

Figure: Observed liver model.

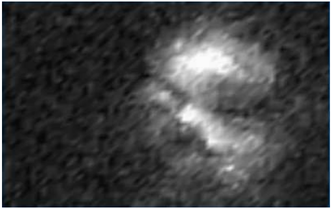

Figure: Card observed with PMD19k.

n=	1	10	20	50
none	162.9	46.7	33.8	17.9
gauss	89.6	31.8	18.4	14.9
median(3x3)	70.4	27.9	21.8	14.8
median(5x5)	73.2	28.4	18.8	11.5

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 liver model. (Observed part marked black.)

Figure: Observed liver model.

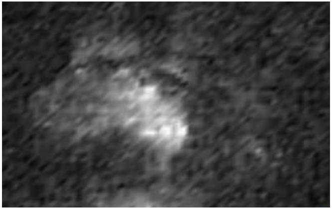

Figure: Card observed with PMD19k.

n=	1	10	20	50
none	91.3	29.6	22.4	12.5
gauss	41.7	12.7	10.5	5.4
median(3x3)	47.9	15.1	12.1	7.8
median(5x5)	36.2	11.5	8.4	5.5

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

Conclusion: Remarks on current state and the structure of an efficient ToF endoscopy group

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.

The end

Thank you for your attention.
Questions?