Contributions of Time-of-Flight cameras

for Biomedical Applications

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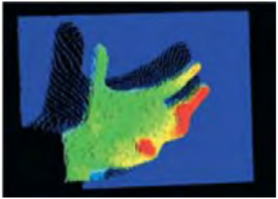
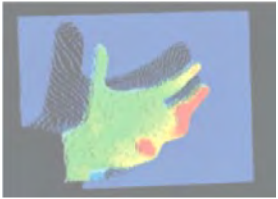
Content



Overview



State of the Art

Time-of-Flight (ToF) technology

- Lateral resolution: 120×160 pixel
- Depth resolution: 3 mm
- Wavelength: 870 nm
- Pixel dimension: $40\mu m \times 40\mu m$
- Modulation frequency: 20 MHz ($\Rightarrow \lambda = 15m$)
- Frame rate: >12 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: 20 MHz ($\Rightarrow \lambda = 15m$)
- Frame rate: >25 fps

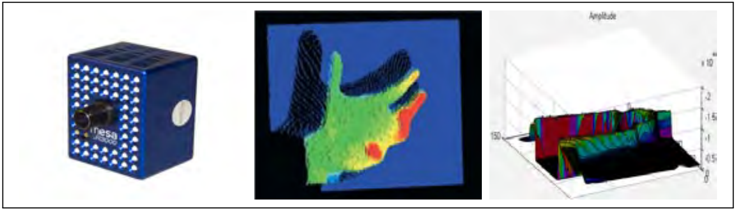
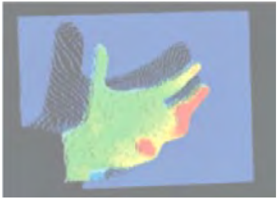


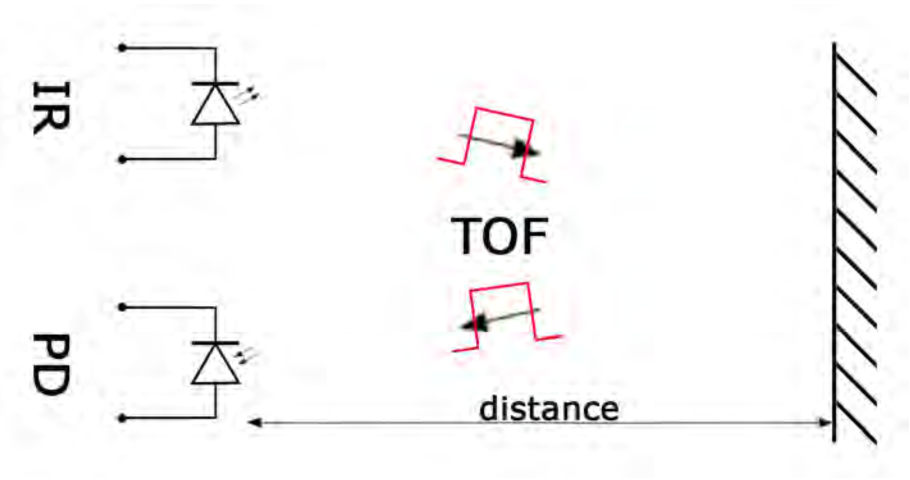
Figure: ToF-camera and example images

Overview



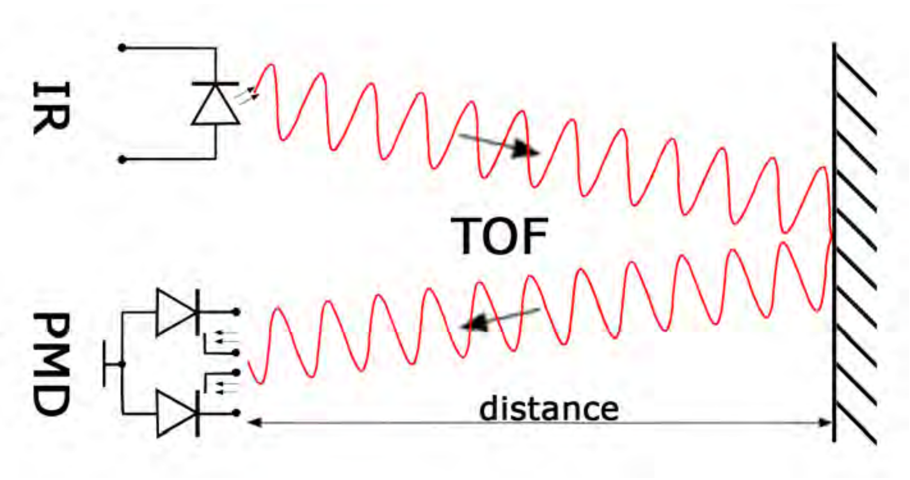
Time-of-flight principle

Pulsed modulation



Time-of-flight principle

Continuous wave modulation



Time-of-flight principle

Continuous wave modulation

- Infra-red light with amplitude modulation using a modulation frequency f_{mod} is sent out by the camera (active illumination), scattered by the object and received again by the camera after a **time of flight** τ_d.
- The camera measures the **phase difference** φ_d between the sent signal $g_k(t)$ with phasing φ_T and the reflected and received wave $s_d(t) \sim g_k(t - \tau_d)$ with phasing φ_R.

$$\varphi_d = \varphi_R - \varphi_T = 2\pi f_{mod} \tau_d \quad (1)$$

- Assuming constant speed of light c the **distance** d is proportional to the phase shift φ_d of emitted and reflected wave:

$$d = \frac{c \cdot \varphi_d}{4\pi \cdot f_{mod}} \quad [\textit{Heinol } 2001] \quad (2)$$

Time-of-flight principle

Measurement cycles

- The phase difference is measured by **sampling the received signal** at N equidistant measurement points. This can be realised by a **stepwise increased phase shift** $\bar{\omega}\tau_k$ of the electrical reference signal:

$$\bar{\omega}\tau_k = \frac{2\pi}{N} \cdot (k-1) \;\; \textit{with} \;\; k = 1, 2, .., N \;\; [\textit{Luan}\, 2001] \tag{3}$$

For normally applied $N = 4$ this means an iterative phase shift by 90° with $\bar{\omega}\tau_1 = 0^\circ$ and $\bar{\omega}\tau_4 = 270^\circ$

Time-of-flight principle

Correlation function

- With the **correlation function** $c(\tau_k) = s_d(t) \otimes g_k(t + \tau_k)$

$$c(\tau_k) = \frac{a}{2} \cdot cos(\varphi_d + \bar{\omega}\tau_k) \quad [Lange\ 2000] \tag{4}$$

and the **voltage dependency**

$$U_k \sim K + c(\tau_k) \quad (K:\ background\ illumination\ influence) \tag{5}$$

the resulting voltages U_k can be computed as

$$\begin{aligned} U_1 &\sim K + \tfrac{a}{2} \cdot cos(\varphi_d), \quad & U_2 &\sim K - \tfrac{a}{2} \cdot sin(\varphi_d), \\ U_3 &\sim K - \tfrac{a}{2} \cdot cos(\varphi_d), \quad & U_4 &\sim K + \tfrac{a}{2} \cdot sin(\varphi_d). \end{aligned} \tag{6}$$

Time-of-flight principle

Results

- Thus a pair of phase shift depending **voltage differences** ΔU_{31} and ΔU_{24} can be build:

$$\begin{aligned} \Delta U_{24} &= U_2 - U_4 = -a \cdot sin(\varphi_d) \\ \Delta U_{31} &= U_3 - U_1 = -a \cdot cos(\varphi_d) \end{aligned} \tag{7}$$

- The relation of these two voltage differences is depending on φ

$$\frac{\Delta U_{24}}{\Delta U_{31}} = tan(\varphi_d) \tag{8}$$

but without knowledge of the unit circle quadrant the common arcustangens function is not sufficient to compute φ unambiguously for the range of values between 0 and 2π .

Time-of-flight principle

Results

- Using the two-argument function atan2 to handle the ambiguity and shifting the results from a range of $-\pi ... \pi$ back to $0 ... 2\pi$ one finally can compute the **phase shift** φ_d:

$$\varphi_d = atan2\left(\Delta U_{24}, \Delta U_{31}\right) + \pi \tag{9}$$

- **Amplitude** A depends as well on ΔU_{24} and ΔU_{31}

$$A \sim \frac{\sqrt{\Delta U_{24}^2 + \Delta U_{31}^2}}{2} \tag{10}$$

- **Offset** K can be computed with voltages $U_1 ... U_4$

$$K \sim \frac{U_1 + U_2 + U_3 + U_4}{4} \tag{11}$$

ToF accuracy

Illumination requirements

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

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

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
A :	illuminated area		

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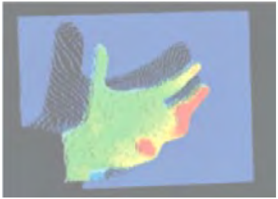

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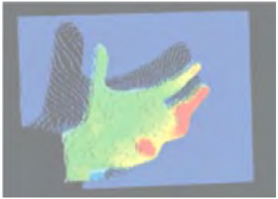


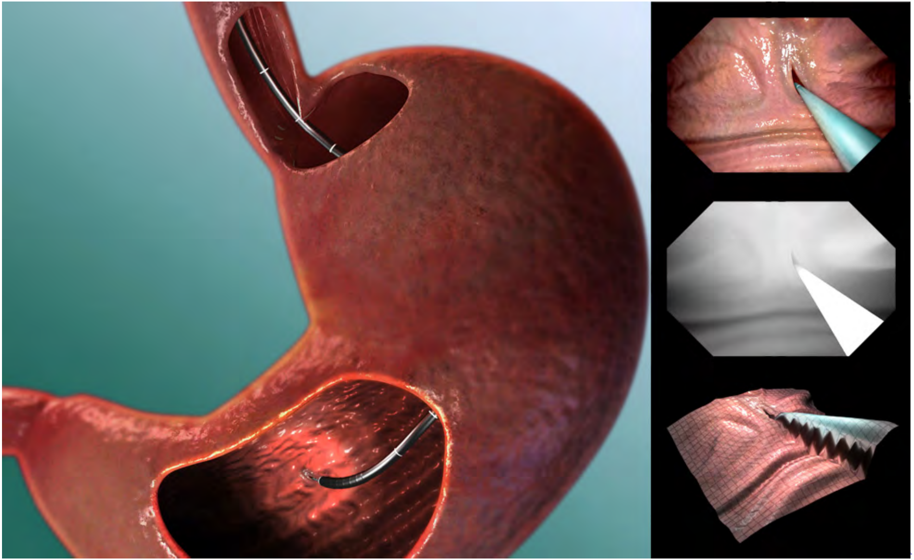
Idea of MUSTOF

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

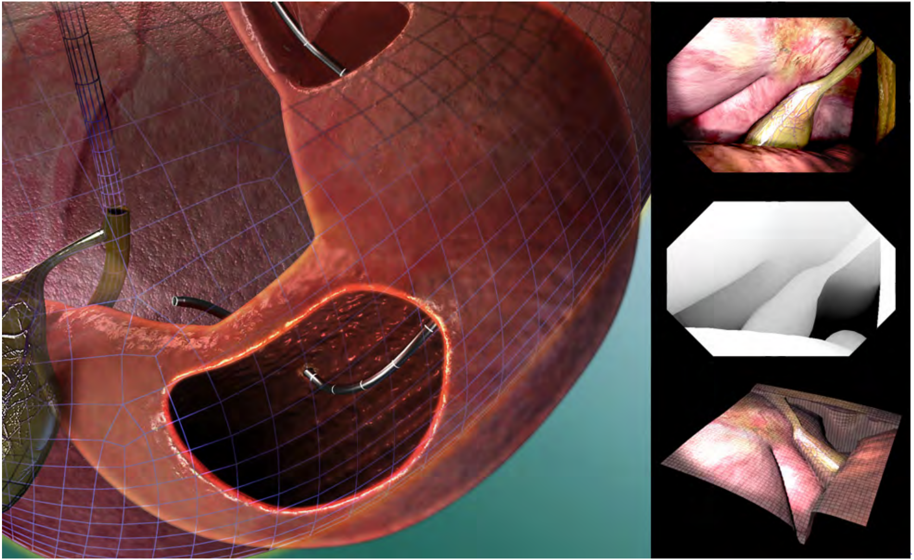
Navigation support - Off-axis view

Finding the entry point to the peritonial cavity



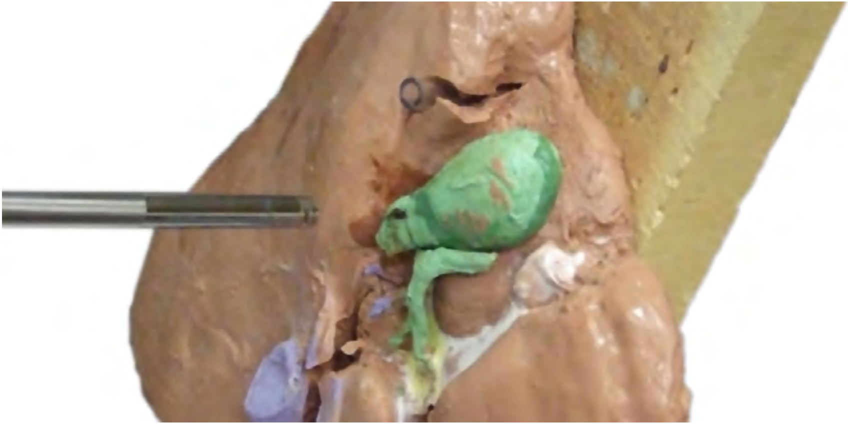
Navigation support - Collision prevention

Finding the entry point to the peritonial cavity



Preliminary results

Liver phantom with gall bladder



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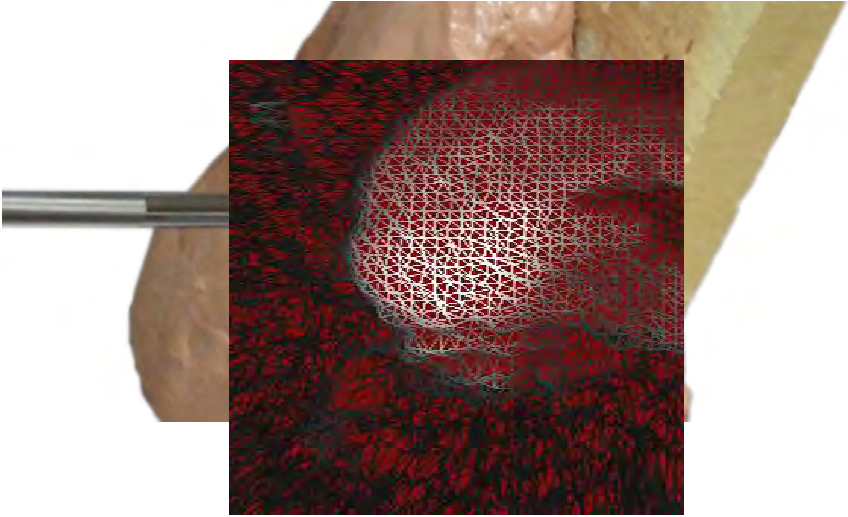

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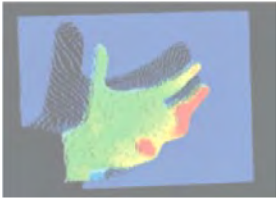
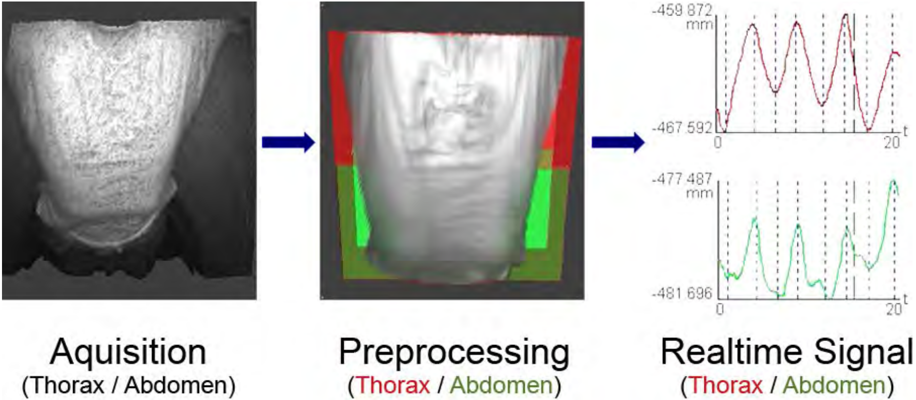


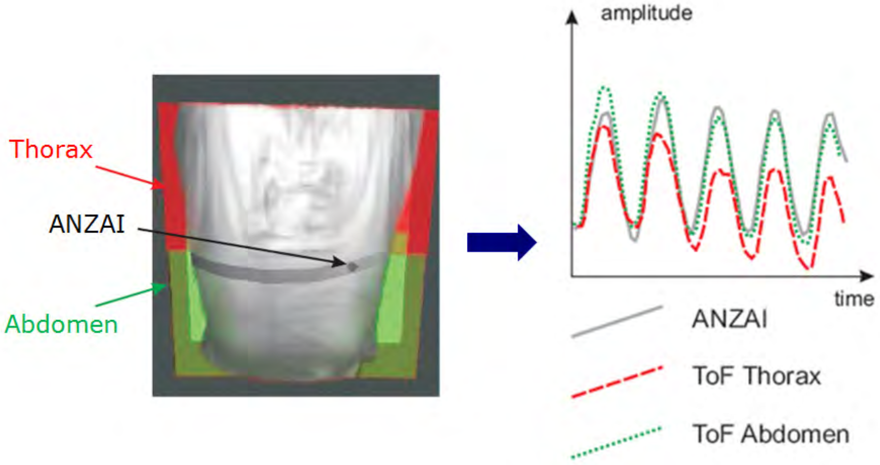
ToF respiratory motion gating

Thorax and Abdomen



ToF respiratory motion gating

Evaluation



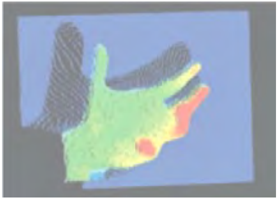
ToF respiratory motion gating

Evaluation

PET Scanner

Lab Setup

Overview

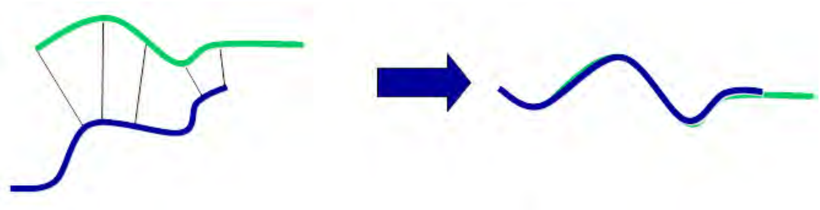


ToF patient positioning

Segmentation and registration

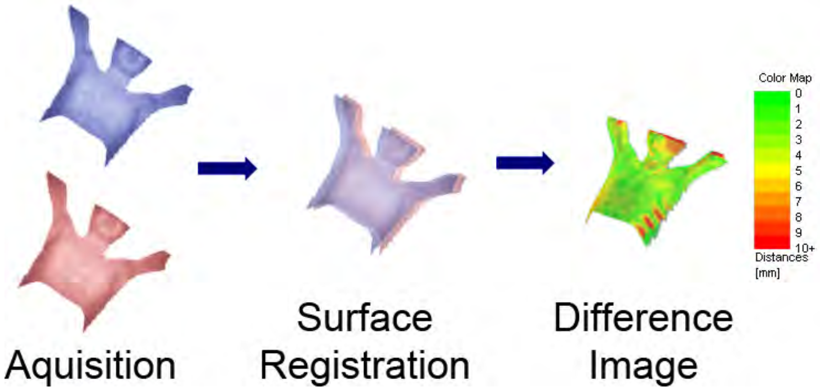
Segmentation

Registration



ToF Patient Positioning

Difference Image



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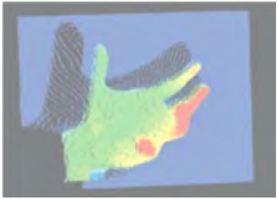
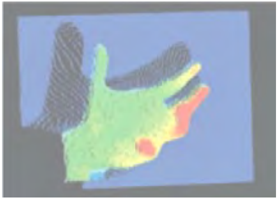


Conclusion

ToF cameras are off-the-shelf technology.

- 3-D endoscopy to provide an enhanced field of view and real-time collision prevention
  → Getting online distance information and computing off-axis view or reconstructed area by stitching
- ToF sensor for respiratory motion gating
  → Competitive approach improving PET, 4-D CT,...
- Patient positioning using 3-D surface registration
  → Adaption of preoperative CT planning in radiotherapy

Overview

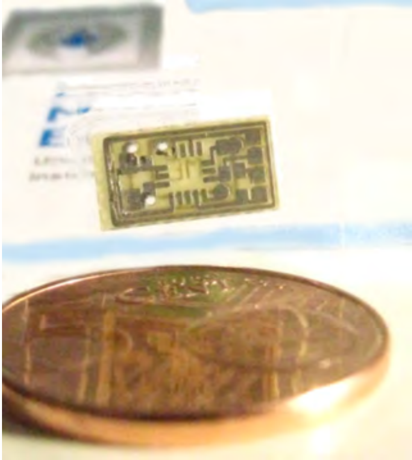


Outlook

Solution for loss of spatial orientation

Real-time information of spatial orientation by measuring gravity

- using MEMS-based inertial devices:
  3-D accelerometers



The End

- Thank you for your attention!
- Any further questions?