Correspondence:

Kurt Höller
Central Institute of Healthcare Engineering (ZiMT)
Friedrich-Alexander-Universitaet Erlangen-Nuernberg (FAU)
Henkestr. 91, D-91052 Erlangen
Tel.: +49 9131 85-26868
Fax: +49 9131 85-26862
kurt.hoeller@fau.de

K. Höller, C. Schaller, D. Tacke, F. Höpfl, and J. Hornegger

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CONTRIBUTIONS OF TIME-OF-FLIGHT CAMERAS FOR BIOMEDICAL APPLICATIONS

K. Höller[1], *C. Schaller*[1], *D. Tacke*[2], *F. Höpfl*[3], *J. Hornegger*[1]

[1]Chair of Pattern Recognition (LME),
Friedrich-Alexander-University Erlangen-Nuremberg,
Martensstr. 3, 91058 Erlangen, Germany

[2]Chair for Microwave Engineering and High Frequency Technology (LHFT),
Friedrich-Alexander-University Erlangen-Nuremberg,
Cauerstraße 9, 91058 Erlangen, Germany

[3]softgate gmbh
Nägelsbachstr. 26, 91052 Erlangen, Germany

hoeller@informatik.uni-erlangen.de

ABSTRACT

New developments of photonic mixer devices (PMD), better known as Time-of-Flight (ToF) cameras, enhance many approaches for a third dimension: with knowledge of the treated person's or object's surface many tasks in vision, visualisation and automatisation are possible whereas 2-D data could not provide enough information. Since this 3-D data are available with up to 40 fps a new dimensions of applications also for challenging medical purposes is opened. One of the most interesting approaches is a hybrid imaging system that combines a conventional CCD camera for color information and a ToF camera for depth information. But also ToF based systems for respiratory motion gating and patient positioning seem to be promising methods. A brief survey of these challenges will be given in this summary.

Index Terms— Time-Of-Flight (ToF), Respiratory Gating, Registration, Positioning, MUSTOF endoscopy

Introduction

In medical applications 3-D information can be acquired by endoscopic ultrasound [1], magnetically anchored instruments [2] or optical approaches. Thereby passive optical methods like stereo vision [3], structure from motion (SfM) [4] or shape from shading (SFS) [5] are known. Active optical methods however make use of pattern projection approaches [6] or consecutive illumination with varied colors (SPARC) [7]. Recently, a new emerging imaging technology called Time-of-Flight (ToF) is available. In contrast to all previous approaches, ToF cameras (e.g. offered by MESA Imaging AG or PMDTechnologies GmbH, fig. 1) provide surface information in real-time nearly independent of calculating capacity or feature clearness.

Fig. 1. MESA SR-3000 (l) and PMD 19K (r)

ToF sensor for acquisition of 3-D data

This new technology uses a single sensor which is feasible to acquire a 3-D surface model in real-time. ToF cameras illuminate the scene actively with an optical reference signal. Usually, the emitted light is part of the non-visible area of the spectrum in the near infrared spectral range (fig. 2).

Assuming constant speed of light c and amplitude modulation frequency f_{mod} the distance d is proportional to the phase shift φ_d of emitted and reflected wave:

$$d = \frac{c \cdot \varphi_d}{4\pi \cdot f_{mod}} \quad [8] \tag{1}$$

To get a distance value for each ToF pixel the modulation phase shift of the reflected optical wave $s(t)$ has to be compared with an electrical reference signal $g(t)$ which has basically the same phasing as the optical signal at the moment of emission. The reflected wave that generates

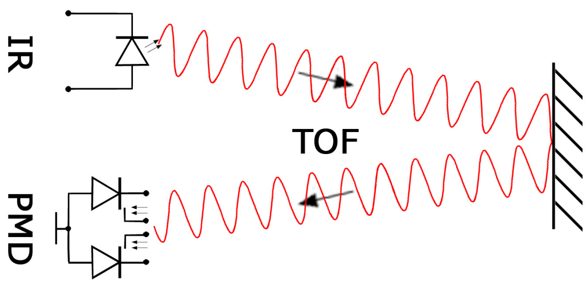

Fig. 2. Principle of emitted and rejected wave with distance depending time of flight and phase shift

electrons in the photoactive zone of each pixel however has a distance depending phasing. To compute this phase difference there are carried out $N \geq 3$ (in common 4) measurement cycles with a certain equal duration (integration time) and a stepwise increased phase shift $\bar{\omega}\tau_k$ of the electrical reference signal:

$$\bar{\omega}\tau_k = \frac{2\pi}{N} \cdot (k-1) \;\; with \;\; k = 1, 2, .., N \;\; [9] \qquad (2)$$

Each variation of $\bar{\omega}\tau_k$ causes a different charge generated within the integration time. With the correlation function $c(\tau_k) = s(t) \otimes g(t) = \frac{a}{2} \cdot cos(\varphi_d + \bar{\omega}\tau_k)$ [10] and the resulting voltages $U_k \sim K + c(\tau_k)$ (K: background illumination influence) a pair of phase shift depending voltage differences ΔU_{31} and ΔU_{24} can be build for $N = 4$:

$$\frac{U_2 - U_4}{U_3 - U_1} = \frac{-a \cdot sin(\varphi_d)}{-a \cdot cos(\varphi_d)} = \frac{\Delta U_{24}}{\Delta U_{31}} \qquad (3)$$

Using a two-argument function to handle the ambiguity of the tangens function for the range of values between 0 and 2π one finally can compute the phase shift φ_d:

$$\varphi_d = atan2\,(\Delta U_{24}, \Delta U_{31}) + \pi \qquad (4)$$

Currently, ToF chips with this function principle can achieve lateral resolutions of up to 176x144 pixels, frame rates of 15-40 fps and z-resolutions within 1 mm.

3-D enhanced endoscopy

Several approaches with computer-assisted surgical systems [11] require additional 3-D information. Registered with preoperative CT or MR data it may provide information on position and orientation of the robotic device or endoscope, show hidden organs or vessels by augmented reality, extend and virtually rotate the field of view and enable efficient collision prevention. An approach to face this challenge is the acquisition of 3-D information directly via the endoscope with a hybrid imaging system. Parallel to the CCD camera a Time-of-Flight (ToF) system is integrated (fig. 3).

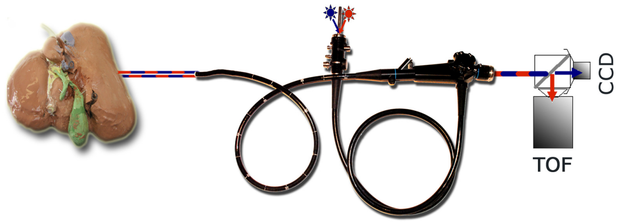

Fig. 3. White-light and modulated IR light are coupled in the endoscope's illumination channel, the reflected portions attain through the image channel to a narrow band beam splitter where the IR fraction is deflected to the ToF camera wheras the remaining part passes to the CCD camera

Accordingly, the name Multisensor-Time-of-Flight endoscope (MUSTOF endoscope) was chosen [12]. Therefore sensor calibration, image reconstruction, feature extraction and volume registration are required [13]. Since MUSTOF endoscopy gives a third dimension to endoscopic images in real-time, those algorithms can be processed fast enough by now. To compensate the high optical attenuation of endoscopic systems, a much more efficient illumination unit with laser diodes had to be designed [14].

ToF sensor for respiratory motion gating

Current methods to account respiratory motion use 1-D surrogate signals to determine respiratory phases [15]. Using this information it is possible to either reconstruct 4-D CT volumes or to apply tumor tracking/gating procedures for cancer treatment based on the surrogate signal [16]. The sensor's high lateral resolution allows defining multiple regions of interest to compute an anatomy-adaptive multidimensional respiratory signal from 3-D surface measurements without the use of markers. We are able to compute a respiratory signal for both the thorax and the abdomen in realtime (~ 15fps) with a standard PC hardware (Pentium M 1.0 GHz)(fig. 4).

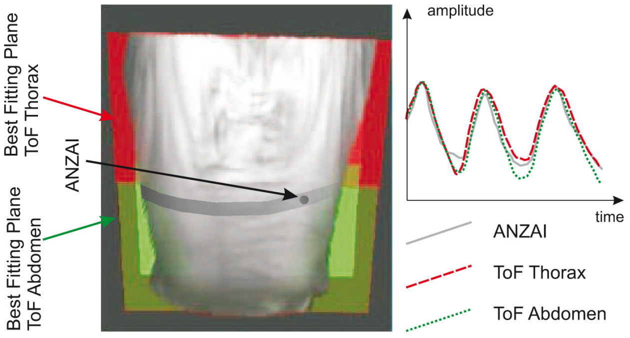

Fig. 4. 3D model of the automatically segmented upper part of the body of a patient. The colored planes are clipping planes used to determine two independent respiratory signals (red: chest; green: abdomen)

Comparing a ToF based respiratory signal with the signal acquired by a commercially available external respiratory gating system (ANZAI Medical Co.) an average correlation coefficient of 0.88 could be achieved.

Patient positioning using 3-D surface registration

Patient positioning is a crucial issue in the field of radiotherapy. In a common workflow, a planning CT scan of the patient is acquired a few days earlier in order to plan the treatment. Right before it starts, the patient has to be positioned accurately in the same way to ensure the treatment plan can be applied correctly [17]. Now a patient's position can be corrected by acquiring body surfaces using a ToF sensor. Given a surface measurement of the patient's body acquired during the planning CT scan and a second one acquired right before or even repeatedly during the treatment session, the patient's misalignment can be identified and corrected. The surface matching process is divided into segmentation and registration processes. Before the two point sets are registered, the patient's body has to be separated from the background. After this preprocessing step an iterative closest point (ICP) algorithm is applied to the datasets in order to determine translation and rotation parameters to correct the position of the patient (fig. 5).

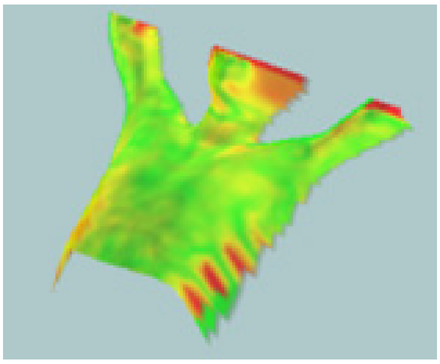

Fig. 5. Evaluation result: The picture shows a difference image between a reference surface and a moving surface. Green colors indicate an error of 0 mm, wheras red indicates an error of more than 10 mm

Current results show that for rigid phantoms it is possible to obtain a correct realignment of ± 2 mm.

Discussion

ToF cameras are off-the-shelf technology. Since automotive and consumer electronics industry are heavily interested in this emerging technology lot of research investment is allocated to improve the so far developed chip design. Currently a typical ToF camera is available for about 5.000 Euros. But if automotive and consumer applications enable large-scale production, prices will rapidly decline and innovation cycles will be quite short. Even if prices are too high for consumer market at the moment, the presented medical applications are auspicious approaches to improve actually provided health care. However MUSTOF endoscopy is a really exciting and high-potential project it still will take some time and lot of research to solve all hardware and sensor fusion tasks. Even the patient positioning system has some non-trivial algorithmic questions. Quite simple but certainly helpful right from the start is the respiratory gating setup, since useful and important data are acquired by a simple way.

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