

# Time-of-Flight Sensors in Computer Graphics

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## Abstract

*A growing number of applications depend on accurate and fast 3D scene analysis. Examples are model and lightfield acquisition, collision prevention, mixed reality, and gesture recognition. The estimation of a range map by image analysis or laser scan techniques is still a time-consuming and expensive part of such systems.*

*A lower-priced, fast and robust alternative for distance measurements are Time-of-Flight (ToF) cameras. Recently, significant advances have been made in producing low-cost and compact ToF-devices, which have the potential to revolutionize many fields of research, including Computer Graphics, Computer Vision and Human Machine Interaction (HMI).*

*These technologies are starting to have an impact on research and commercial applications. The upcoming generation of ToF sensors, however, will be even more powerful and will have the potential to become “ubiquitous real-time geometry devices” for gaming, web-conferencing, and numerous other applications. This STAR gives an account of recent developments in ToF-technology and discusses the current state of the integration of this technology into various graphics-related applications.*

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism I.3.8 [Computer Graphics]: Applications

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## 1. Introduction

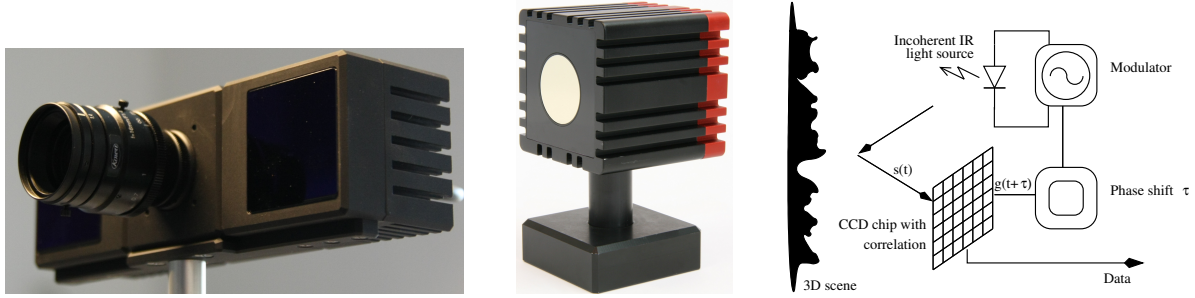
Acquiring 3D geometric information from real environments is an essential task for many applications in computer graphics. Prominent examples such as cultural heritage, virtual and augmented environments and human machine interaction, e.g. for gaming, clearly benefit from simple and accurate devices for real-time range image acquisition. However, even for static scenes there is no low-priced off-the-shelf system that provides full-range, high resolution distance information in real-time. Laser scanning techniques, which merely sample a scene row by row with a single laser device, are rather time-consuming and therefore impracticable for dynamic scenes. Stereo vision camera systems suffer from the inability to match correspondences in homogeneous object regions.

Time-of-Flight (ToF) technology, a recent development in imaging hardware, opens new possibilities. Unlike other 3D systems, the ToF sensor is a very compact device which already fulfills most of the above stated features desired

for real-time distance acquisition. There are two main approaches currently employed in ToF technology. The first one utilizes modulated, incoherent light, and is based on a phase measurement that can be implemented in standard CMOS or CCD technology [XSH\*98, OBL\*05]. The second approach is based on an optical shutter technology, which was first used for studio cameras [IY01] and was later developed into miniaturized cameras such as the new Zcam [YIM07].

Within the last three years, the number of research activities in the context of ToF sensors increased dramatically. Taking a look at the publications cited in this STAR we find an increase from the year 2006 to 2008 by factor of 8 to 9. While the initial research focused on more basic questions like sensor characteristics and the application of ToF sensors for the acquisition of static scenes, other application areas have recently come into focus, e.g. human machine interaction and surveillance.

This STAR aims to make the computer graphics com-



**Figure 1:** Left: PMDTec/ifm electronics CamCube sensor; Middle: MESA SR4000 sensor; Right: The ToF phase-measurement principle.

community aware of a rapidly developing and promising sensor technology and it gives an overview of its first applications to scene reconstruction, mixed reality/3D TV, user interaction and light fields. Moreover, recent results and ongoing research activities are presented to illustrate this dynamically growing field of research.

The STAR first gives an overview of basic technological foundations of the ToF measurement principles (Section 2) and presents current research activities (Section 3). Sections 4 and 5 discuss sensor calibration issues and basic concepts in terms of image processing and sensor fusion. Section 6 focuses on applications for geometric reconstruction, Section 7 on dynamic 3D-keying, Section 8 on interaction based on ToF cameras, and Section 9 on interactive light field acquisition. Finally, we draw a conclusion and give a perspective on future work in the field of ToF sensor based research and applications.

## 2. Technological Foundations

### 2.1. Intensity Modulation Approach

This ToF-principle is used by various manufacturers, e.g. PMDTec/ifm electronics ([www.pmdtec.com](http://www.pmdtec.com); Fig. 1, left), MESA Imaging ([www.mesa-imaging.ch](http://www.mesa-imaging.ch); Fig. 1, middle) and Canesta ([www.canesta.com](http://www.canesta.com)).

The intensity modulation principle (see Fig. 1, right, and [Lan00]) is based on the on-chip correlation (or mixing) of the incident optical signal  $s$ , coming from a modulated NIR illumination and reflected by the scene, with its reference signal  $g$ , possibly with an internal phase offset  $\tau$ :

$$c(\tau) = s \otimes g = \lim_{T \rightarrow \infty} \int_{-T/2}^{T/2} s(t) \cdot g(t + \tau) dt.$$

For a sinusoidal signal, e.g.

$$g(t) = \cos(\omega t), \quad s(t) = b + a \cos(\omega t + \phi)$$

where  $\omega$  is the modulation frequency,  $a$  is the amplitude of the incident optical signal,  $b$  is the correlation bias and  $\phi$  is

the phase offset relating to the object distance, some trigonometric calculus yields  $c(\tau) = \frac{a}{2} \cos(\omega\tau + \phi) + b$ .

The demodulation of the correlation function  $c$  is done using samples of the correlation function  $c$  obtained by four sequential phase images with different phase offset  $\tau$ :  $A_i = c(i \cdot \frac{\pi}{2})$ ,  $i = 0, \dots, 3$ :

$$\phi = \arctan 2(A_3 - A_1, A_0 - A_2), \quad I = \frac{A_0 + A_1 + A_2 + A_3}{4},$$

$$a = \frac{\sqrt{(A_3 - A_1)^2 + (A_0 - A_2)^2}}{2},$$

where  $I$  is the intensity of the incident NIR light. Now, from  $\phi$  one can easily compute the object distance  $d = \frac{c}{4\pi\omega} \phi$ , where  $c \approx 3 \cdot 10^8 \frac{m}{s}$  is the speed of light. Current devices acquire range maps at 20 FPS, and some of them support *Suppression of Background Intensity (SBI)*, which facilitates outdoor applications. If the sensor is equipped with SBI, the intensity  $I$  mainly reflects the incident active light.

ToF sensors use standard optics to focus the reflected active light onto the chip. Thus, classical intrinsic calibration is required to compensate effects like shifted optical centers and lateral distortion. Furthermore, using ToF sensors based on the intensity modulation approach involves major sensor-specific challenges:

**Low Resolution:** Current sensors have a resolution between  $64 \times 48$  and  $204^2$  (PMDTec's "CamCube", see Fig. 1, left). This resolution is rather small in comparison to standard RGB- or grayscale-sensors.

**Systematic Distance Error:** Since the theoretically required sinusoidal signal is practically not achievable, the measured depth does not reflect the true distance but comprises a systematic error, also called "wiggling" (see Fig. 3, left).

**Intensity-related Distance Error:** Additionally, the measured distance (in the raw data) is influenced by the total amount of incident light. This fact results from different physical effects in the ToF camera, both the semiconductor detector and the camera electronics. However, this is

not a generic ToF problem and some manufacturers seem to have found solutions to this problem.

**Depth Inhomogeneity:** The mixing process in a pixel that observes a region with inhomogeneous depth results in superimposed signals and leads to wrong distance values (“flying pixels”), e.g. at object boundaries (see Fig. 3, right).

**Motion Artifacts:** The four phase images  $A_i$  are acquired successively, thus sensor or object motion leads to erroneous distance values at object boundaries (see Fig. 3, right).

**Multiple Reflections:** Especially when the camera is used in enclosures and cluttered environments, the distance measurement can be falsified due to superposition of direct reflected active light with active light that travels one or more indirect paths.

**General Aspects of Active Systems:** Active illumination ToF sensors contain error sources that are common to many other active sensing systems. Firstly, using several sensors in parallel leads to interference problems, i.e. the active illumination of one camera influences the result of all other cameras. Secondly, object areas with extremely low reflectivity lead to a low signal. Highly specular objects or reflections in the surroundings lead to an erroneous distance measurement due to indirect ray paths. And finally, the energy of the reflected light decreases with the square of the distance.

From a theoretical perspective, the systematic distance error can be removed if the correlation function  $c(\tau)$  is represented including higher Fourier modes [Lan00, Rap07], i.e.

$$c(\tau) = \sum_{k=0}^l c_k \cos(k(\omega\tau + \phi) + \theta_k).$$

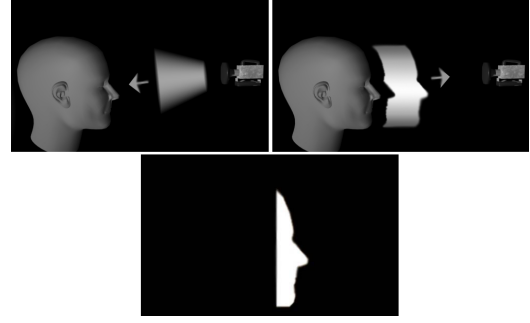
A least squares optimization over  $N \geq 2l + 1$  samples of the correlation function, i.e. phase images  $A_i = c(i \cdot \frac{2\pi}{N})$ , leads to following phase demodulation scheme:

$$\phi = \arg \left( \sum_{i=0}^{N-1} A_i e^{-2\pi i k \frac{i}{N}} \right).$$

In practice, extending the demodulation scheme for higher frequencies is impracticable as the number of required phase images as well as the calculation effort for the demodulation increase dramatically. Furthermore, the higher number of samples would result in an increase of motion artifacts.

## 2.2. Optical Shutter Approach

This alternative ToF-principle is based on the indirect measurement of the time of flight using a fast shutter technique [IY01, YIM07]. The basic concept uses a short NIR light pulse  $[t_{\text{start}}, t_{\text{stop}}]$ , which represents a depth range of interest (“light wall”, see Fig. 2, top-left). The optical signal is reflected by the scene objects leading to a “distorted” light wall, resembling the objects’ shapes. A shutter in front



**Figure 2:** The shutter principle: A “light wall” is emitted from the sensor (top-left) and reflected by the object (top-right). Gating the reflected optical signal yields distance-related portions of the “light wall”, which are measured in the CCD pixels [IY01].

of a standard CCD sensor cuts the front (or rear) portion of the optical signal at the gating time  $t_{\text{gate}} = t_{\text{start}} + \Delta_t$ . The resulting intensity  $I_{\text{front}}$  is proportional to the distance of the related segment of the object’s surface. This normalizes the object’s reflectivity as well as the attenuation of the active light due to the object’s distance. The distance measurement relates to the “distance time range”  $[t_{\text{min}}, t_{\text{max}}] = [\Delta_t, t_{\text{stop}} - t_{\text{start}}]$  and the relation  $I_{\text{front}}/I_{\text{total}}$  of the total reflected signal  $I_{\text{total}}$  and the front cut, i.e.

$$d = (1 - \alpha)d_{\text{min}} + \alpha d_{\text{max}}, \quad \alpha = \frac{I_{\text{gate}}}{I_{\text{total}}},$$

$$d_{\text{min}} = c \cdot t_{\text{min}}, \quad d_{\text{max}} = c \cdot t_{\text{max}}, \quad c \approx 3 \cdot 10^8 \frac{\text{m}}{\text{s}}$$

Distances below  $d_{\text{min}}$  and above  $d_{\text{max}}$  cannot be measured in a single exposure. Thus, if larger depth ranges need to be observed, several exposures are used with varying gating parameters [GKOY03a].

Regarding the error sources for the sensor type, almost all challenges stated in Sec. 2.1 should be present as well. However, because very few research results on this sensor are publicly available at present, the specific sensor characteristics is not completely revealed.

## 2.3. ToF-Sensor Simulation

In the context of the development of ToF sensors and their applications, ToF-simulators play an important role. Very flexible but rather inefficient simulation approaches are based on general-purpose simulation tools such as MATLAB [PLHK07]. A real-time simulator incorporating major sensor errors, i.e. the systematic distance error, flying pixels and motion artifacts, has been implemented using the parallel GPU programming paradigm [KKP07, KK09]. This allows the direct replacement of sensors in real-time processing pipelines in order to evaluate new sensor parameters.

### 3. Current Research Projects and Workshops

The field of real-time ToF sensor based techniques is very active and covers further areas not discussed here. Its vividness is proven by a significant number of currently ongoing medium and large-scale research projects, e.g.

**Dynamic 3D Vision (2006-2010):** A bundle of 6 projects funded by the German Research Association (DFG). Research foci are multi-chip 2D/3D-sensors, dynamic scene reconstruction, object localization and recognition, and light field computation ([www.zess.uni-siegen.de/pmd-home/dyn3d](http://www.zess.uni-siegen.de/pmd-home/dyn3d)).

**ARTTS (2007-2010):** “Action Recognition and Tracking based on Time-of-Flight Sensors” is EU-funded ([www.artts.eu](http://www.artts.eu)). The project aims to develop (i) a new ToF camera that is smaller and cheaper, (ii) a combined HDTV/ToF camera, and (iii) algorithms for tracking and action recognition with a focus on multi-modal interfaces and interactive systems.

**Lynkeus (2006-2009):** Funded by the German Ministry of Education and Research, BMBF, ([www.lynkeus-3d.de](http://www.lynkeus-3d.de)), this project strives for higher resolution and robust ToF sensors for industry applications, e.g. in automation and robot navigation. Lynkeus involves 20 industry and university partners.

**3D4YOU (2008-2010):** An EU-funded project for establishing the 3D-TV production pipeline, from real-time 3D film acquisition, data coding and transmission, to novel 3D displays at the homes of the TV audience ([www.3d4you.eu](http://www.3d4you.eu)). 3D4YOU utilizes ToF range cameras to initialize the depth estimation from multiple high-definition cameras to compute a 3D scene representation.

**MOSES (2008-2012):** The research school “Multi-Modal Sensor Systems for Environmental Exploration (MOSES)” covers various aspects of sensor-based applications including ToF-based human machine interaction and multi sensor fusion ([www.zess.uni-siegen.de/ipp\\_home/moses](http://www.zess.uni-siegen.de/ipp_home/moses)).

**Research Training Group “Imaging New Modalities” (2009-2014):** This DFG funded project aims at excellence and innovation in the area of sensor-based civil security applications including ToF-based scene observation ([www.grk1564.zess.uni-siegen.de](http://www.grk1564.zess.uni-siegen.de)).

Furthermore, a series of workshops have been held in the last years and will be held in the near future, documenting the worldwide productivity of researchers in this field.

**IEEE Int. Symp. on Signals, Circuits & Systems, 2007,** half-day session on “Algorithms for 3D time-of-flight cameras”, Iasi, Romania.

**Symp. German Ass. for Patt. Recogn. (DAGM), 2007,** full-day workshop on “Dynamic 3D Imaging”, Heidelberg, Germany.

**IEEE Comp. Vision & Patt. Recongn. (CVPR), 2008,** full-day workshop on “Time of Flight Camera based Computer Vision (TOF-CV)”, Anchorage, USA.

**Symp. German Ass. for Patt. Recogn. (DAGM), 2009,** full-day workshop on “Dynamic 3D Imaging”, Jena, Germany.

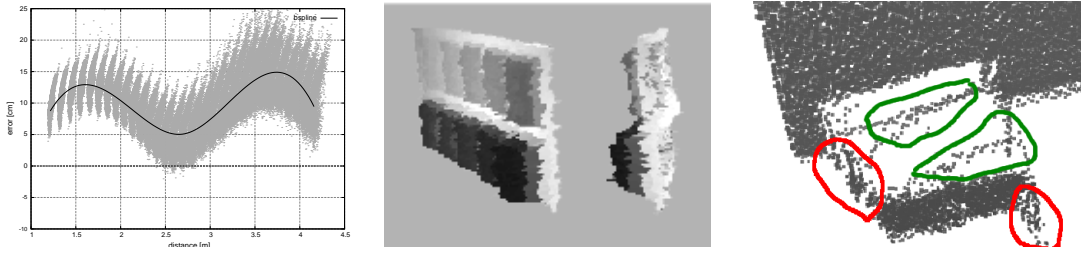
### 4. Calibration

As mentioned in Sec. 2, ToF sensors require lateral calibration. For ToF sensors with relatively high resolution, i.e.  $160 \times 120$  or above, standard calibration techniques can be used [LK06]. For low-resolution sensors, an optimization approach based on analysis-by-synthesis has been proposed [BK08]. However, this technique requires a sensor model incorporating the systematic distance error for accurate image reconstruction (see below).

Considering the systematic error of ToF sensors, the question of the acquisition of reference data (“ground truth”) arises. Early approaches used track lines [LK06, KRG07], which requires rather cost-intensive equipment. In the robotic context, the known position of the robot’s tool center point can be used to locate the sensor in a global reference frame [FM08, FH08]. Alternative techniques use vision-based approaches to estimate the extrinsic parameters of the sensor with respect to a reference plane, e.g. a checkerboard [LK07]. However, as for the lateral calibration, more complex approaches are required in case of low-resolution ToF sensors.

Regarding the systematic distance error, the first approaches assumed a linear deviation with respect to the object’s distance [KS06]. A closer look at the error reveals a nearly periodic, sine-like function (see Fig. 3, left). This systematic depth error can be corrected using look-up tables [KRG07] or correction functions like b-splines [LK06]. In [LK06] an additional per-pixel adjustment is used to cope with individual pixel errors. A very comprehensive study of various ToF sensors has been carried out in [Rap07]. One major result of this study is that the systematic error behaves quite similarly for different sensor types. Differences appear in the near range (over-saturation).

The noise level of the distance measurement depends on the amount of incident active light. Also, an additional depth error related to the intensity  $I$  is observed, i.e. object regions with low NIR reflectivity have a non-zero mean offset compared to regions with high reflectivity. One approach is to model the noise in the phase images  $A_i$  under the assumption of a linear but varying gain for the phase images  $A_i$  [FB07]. In [LK07] the systematic and the intensity-related errors are compensated using a bivariate correction function based on b-splines directly on the distance values, under the assumption that both effects are coupled. Alternatively, instead of dealing with the intensity value, one can also consult the sensor’s amplitude values  $a$  [RFK08]. Assuming constant environmental effects, homogeneous depth information per pixel and ideal sensors, the amplitude  $a$  and the intensity  $I$  are strongly correlated.



**Figure 3:** Error sources of PMD-based ToF sensors. Left: Systematic distance error for all pixels (grey) and fitted mean deviation (black). Middle: Intensity-related distance error sensing a planar object with varying reflectivity. Right: Motion artifacts (red) and flying pixels (green) for a horizontally moving planar object in front of a wall.

Regarding the intensity images delivered by ToF sensors, [SPH08c] presents an approach to normalize the intensity variation related to the attenuation caused by the active device illumination.

From a practical point of view, a major challenge is the large number of reference data required. Usually, some 15–20 distance measurements are used as ground truth for the systematic error, and some 5–10 measurements are used for different intensities. This results in approximately 60–200 reference data sets that need to be acquired. Current research aims to reduce this heavy burden. To relieve the user from manually collecting this large amount of data, an automatic multi-camera calibration scheme was devised that combines optical camera calibration based on a planar checkerboard calibration object with automatic depth adjustment of the ToF camera in one step [SBK08b]. Starting with checkerboard corner fitting, an iterative intensity and depth fitting of all data minimizes the overall re-projection intensity error, taking into account all internal and external camera parameters, including polynomial fitting for radial and depth distortions. The resulting residual errors are typically well below one pixel. A calibration toolbox can be downloaded from [www.mip.informatik.uni-kiel.de](http://www.mip.informatik.uni-kiel.de).

Regarding the systematic depth error, another approach incorporating an alternative demodulation scheme based on the assumption of a box signal has been introduced [LK08]. Even though the demodulation scheme produces similar errors as the one based on the assumption of a sinusoidal signal, combining both demodulation schemes reduces the overall error when using only as few as four reference measurements.

Whereas the systematic and the intensity-related error are highly non-linear with regard to the distance and incident active light, their dependency on the exposure time can be modeled as constant offset [KRI06, LK07, Rap07].

Multiple reflections are a principal problem in ToF measurements [GAL07]. In [FB08, Fal08] the authors describe a model for multiple reflections as well as a technique for correcting the related measurements. More specifically, the

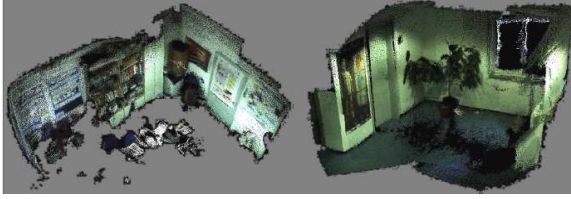
perturbation component due to multiple reflections outside and inside the camera depends on the scene and on the camera construction, respectively. The spatial spectral components consist mainly of low spatial frequencies and can be compensated using a genuine model of the signal as being complex with the amplitude and the distance as modulus and argument. The model is particularly useful if an additional light pattern can be projected onto the object.

Some work has been conducted in the area of the sensor's internal scattering effects. First results in determining the point spread function of ToF sensors are at hand, based on the superposition of Gaussian functions [MDH07] and on empirical scatter models based on reflectance measurements for point reflectors [KKTJ08]. Both works show that the intensity pattern caused by scattering strongly varies across the image plane.

Regarding motion artifacts, the device manufacturers attempt to reduce the latency between the individual exposures for the four phase images, which is mainly caused by the data readout from the chip. However, the problem remains and might be solved by motion-compensated integration of the individual measurements.

## 5. Range Image Processing and Sensor Fusion

Before using the range data from a ToF sensor, usually some pre-processing of the input data is required. To remove outliers, the ToF's amplitude value  $a$  can be used as confidence measure since it represents the accuracy of the on-pixel correlation process. Using a constant amplitude range, e.g. [20%, 80%], one can remove pixels with low accuracy or saturated pixels. However, the amplitude value relates to the amount of incident active light and thus decreases for distant objects and objects at the image boundary, since the active illumination units normally have a radial fall-off in their intensity profile. Thus, different methods like local distance distributions may be used. Furthermore, most applications need to deal with flying pixels, since they represent false geometric information. This can be achieved by applying a bilateral filter to the range data [HSJS08]. Alternatively, edge-



**Figure 4:** Two acquired office scenes using a 2D/3D camera combination (seen from a third person view) [HJS08].

directed resampling technique can be used, combined with an upscaling technique applied to the range image [LLK08].

ToF sensors deliver both distance and intensity values for every pixel. Therefore the distance signal can be used to improve the intensity signal and the intensity signal can be used to correct the distance measurement [OFCB07]. In [LLK08], depth image refinement techniques are discussed to overcome the low resolution of a PMD sensor in combination with an enhancement of object boundaries, which follow approaches from boundary preservation of subdivision surfaces. A bimodal approach using intra-patch similarity and optional color information is presented in [HSJS08]. In [STDT08] the authors introduce a super-resolution approach to handle the low device resolution using depth maps acquired from slightly shifted points of view. Here, the low input depth images are obtained by unknown sensor rotation and the high resolution range image is formulated as the result of an optimization techniques. This approach is not real-time capable.

The statistics of the natural environment are such that a higher resolution is required for color than for depth information. Therefore different combinations of high-resolution video cameras and lower-resolution ToF sensors have been studied.

Many researchers use a binocular combination of a ToF sensor with one [LPL\*07, HJS08, JHS07, LKH07, SBKK07] or with several RGB-cameras [GLA\*08b], enhancing the low resolution ToF data with high resolution color information. This fixated sensor combinations enable the computation of the rigid 3D transformation between the optical centers of both sensors (external calibration) and intrinsic camera parameters of each sensor. Utilizing this transformations the 3D points provided by the ToF camera are co-registered with the 2D image, thus color information can be assigned to each 3D point. A commercial and compact binocular 2D/3D-camera based on the optical shutter approach has been released by 3DV Systems [YIM07].

In many approaches a rather simple data fusion scheme is implemented by mapping the ToF pixel as 3D point onto the 2D image plane resulting in a single color value per ToF pixel [LPL\*07, HJS08, JHS07]. A more sophis-



**Figure 5:** Improvement of range map quality using the shading constraint. From left: Intensity image; lateral view of raw measured surface; and surface reconstructed using the shading constraint in lateral and frontal views.

ticated approach presented in [LKH07] projects the portion of the RGB image corresponding to a representative 3D ToF pixel geometry, e.g. a quad, using texture mapping techniques. Furthermore, occlusion artifacts in the near range of the binocular camera rig are detected. [DT06] improve the resolution of a low-resolution range map by fusing it with a high-resolution color image. Their method exploits the fact that depth discontinuities often co-occur with color or brightness discontinuities; a Markov Random Field (MRF) is used to estimate the high-resolution range map. Yang e.a. [YYDN07] combine a high-resolution color image with a depth image by upscaling depth to color resolution. They apply bilateral filtering and sub-pixel smoothing on the depth data with good results.

There are also a number of monocular systems, which combine a ToF sensor with a conventional image sensor behind a single lens. They have the advantage of making data fusion easier but require more sophisticated optics and hardware. The 3DV VisZcam [IY01] is an early example of a monocular 2D/3D-camera aimed at TV production. A monocular 2D/3D-camera based on the PMD-sensor has been introduced in [LHLW07]. This 2-chip sensor uses a beam-splitter for synchronous and auto-registered acquisition of 2D- and 3D data.

Another research direction aims at combining ToF cameras with classical stereo techniques. In [KS06], a PMD-stereo combination has been introduced to exploit the complementarity of both sensors. In [GAL08], it has been shown that a ToF-stereo combination can significantly speed up the stereo algorithm and can help to manage texture-less regions. The approach in [BBK07] fuses stereo and ToF estimates of very different resolutions to estimate local surface patches including surface normals. A global data fusion algorithm that incorporates belief propagation for depth from stereo images and the ToF depth data is presented by [ZWYD08]. They combine both estimates with a MRF to obtain a fused superior depth estimate.

A recent technique [BHMB08b] for improving the accu-

racy of range maps measured by ToF cameras is based on the observation that the range map and intensity image are not independent but are linked by the *shading constraint*: If the reflectance properties of the surface are known, a certain range map implies a corresponding intensity image. In practice, a general reflectance model (such as Lambertian reflectance) provides a sufficient approximation for a wide range of surfaces. The shading constraint can be imposed by using a probabilistic model of image formation to find a maximum a posteriori estimate for the true range map. The method also allows the reflectivity (or *albedo*) of the surface to be estimated, both globally for an entire object and locally for objects where albedo varies across the surface. The algorithm substantially improves the quality of the range maps, both in terms of objective measures such as RMS error and in subjectively perceived quality (see Fig. 5).

First works investigate *multi-view* setups. A major challenge is to realize a system that hinders the interference of the active ToF sensors. The approaches presented in [KCTT08, GFP08] use different modulation frequencies, however the authors do not discuss the constraints that the different modulation frequencies need to fulfill in order to guarantee noninterference.

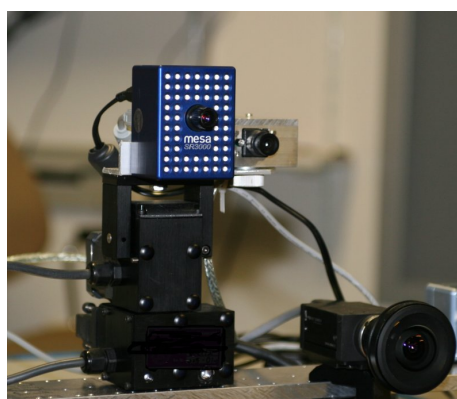
Meanwhile, however, some manufacturers have already implemented more sophisticated active illuminations that make use of binary codes by which different sources can be separated [MB07].

## 6. Geometry Extraction and Dynamic Scene Analysis

ToF cameras are especially well suited to directly capture 3D scene geometry in static and even dynamic environments. A 3D map of the environment can be captured by sweeping the ToF camera and registering all scene geometry into a consistent reference coordinate system [HJS08]. Fig. 4 shows two sample scenes acquired with this kind of approach. For high quality reconstruction, the low resolution and small field of view of a ToF camera can be compensated for by combining it with high-resolution image-based 3D scene reconstruction, for example by utilizing a structure-from-motion (SFM) approach [BKWK07, KBK07]. The inherent problem of SFM, that no metric scale can be obtained, is solved by the metric properties of the ToF-measurements [SBKK07]. This allows to reconstruct metric scenes with high resolution at interactive rates, for example for 3D map building and navigation [PMS\*08]. Since color and depth can be obtained simultaneously, free viewpoint rendering is easily incorporated using depth-compensated warping [KES05]. The real-time nature of the ToF-measurements enables 3D object recognition and the reconstruction of dynamic 3D scenes for novel applications such as free viewpoint TV and 3D-TV. A high-definition TV camera or multi-view rig is combined with a ToF camera to give a depth estimate of the scene. The depth is upscaled and fused like in [YYDN07, ZWYD08], and a layered depth and color map is constructed for each

image frame. This layered depth video is then coded and stored for playback on a 3D auto-stereoscopic display to give glass-less 3D impression to the viewer.

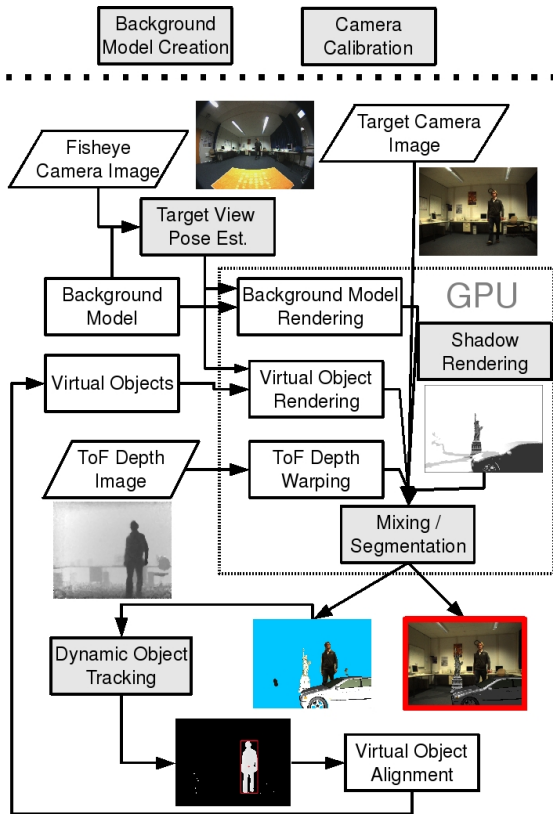
Simultaneous reconstruction of a scene with wide field of view and dynamic scene analysis can be achieved by combining a ToF/color camera pair on a computer-driven pan-tilt unit and by scanning the environment in a controlled manner. While scanning the scene, a 3D panorama can be computed by stitching both depth and the color images into a common cylindrical or spherical panorama. From the center point given by the position of the pan-tilt unit, a 3D environment model can be reconstructed in a preparation phase. Dynamic 3D scene content like a moving person can then be captured online by adaptive object tracking with the camera head [BSBK08]. Fig. 6 shows the technical setup of such a system. Examples can be found in Fig. 8.



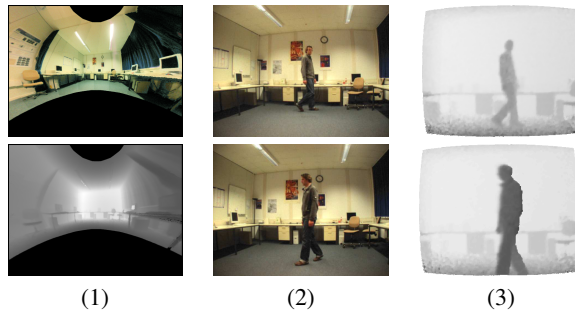
**Figure 6:** Setup comprising of a ToF camera (SwissRanger 3000) mounted together with a CCD firewire camera on a pan-tilt unit and a fisheye camera mounted at the bottom right.

In addition to the color camera, a second camera with fish-eye optics is added to allow easy tracking of the complete system, thus allowing to move freely inside of the scene. The hemispherical view of the fisheye camera is used to locate the current position of the camera rig within the environment even for very long time sequences without position drift [KBK07]. Fig. 7 describes the layout of a complete system that is used to model the scene and to track the dynamic object. The information obtained here can be utilized for example in depth-based keying, object segmentation, shadow computation and general Mixed Reality tasks, as described in Sec. 7.

A number of application oriented contributions based on ToF cameras have been made. In [TBB08], for example, a method for using a ToF camera for detection and tracking of pipeline features such as junctions, bends and obstacles has been presented. Feature extraction is done by fitting cylinders and cones to range-images from inside the pipeline.



**Figure 7:** System for 3D environment modeling, 3D object tracking and segmentation for Mixed Reality applications (from [BSBK08]).



**Figure 8:** Column (1): The texture and the depth image (dark = near, light = far) as panorama after scanning of the environment. For visualization, the panorama is mapped onto a cylindric image. Column (2): Two images out of a sequence of a person walking through the real room with a virtual occluder object. (2) Original image; (3) ToF depth image for depth keying.

ToF cameras have an obvious potential for external sensing in automotive applications. In [AR08] a system design for parking assist and backup has been presented. A further paper [GMR08] uses a RANSAC algorithm for fitting planes to 3D data such as to enable the recognition of curbs and ramps.

Regarding dynamic scene analysis, one of the first ToF-based applications was the so called out-of-position system where the airbag in the car is deployed as a function of head position [FOS\*01]. The application requires the recognition of different seat-occupancy classes like for example adult, child, rear-facing child seat, cargo etc. In addition, the head must be tracked such as to avoid deployment in cases where the head is close to the airbag. In this context, a human body tracker based on Reeb graphs extracted from ToF data has been developed [DCG\*07].

ToF camera systems can be successfully utilized to detect respiratory motion of human persons. Possible applications are emission tomography where respiratory motion may be the main reason for image quality degradation. Three-dimensional, marker-less, real-time respiratory motion detection can be accomplished with available ToF camera systems with an accuracy of 0.1 mm and is clearly competitive with other image based approaches [PSHK08, SPH08a]. Moreover, one can use ToF cameras to monitor respiration during sleep and detect sleep apnea [FID08].

Some medical applications like cancer treatment require a re-positioning of the patient to a previously defined position. ToF cameras have been used to solve the problem by segmentation of the patient body and a rigid 3D-3D surface registration. Tests with human persons yielded registration errors in the millimeter range [ASPH08].

## 7. Dynamic 3D Depth Keying and Shadow Interaction

One application particularly well suited for ToF cameras is real-time depth keying in dynamic 3D scenes. A feature commonly used in TV studio production today is the 2D chroma keying, where a specific background color serves as key for 2D segmentation of a foreground object, usually a person, which can then be inserted in computer generated 2D background. The 2D-approach is limited, however, since the foreground object can never be occluded by virtual objects. An alternative approach for high-resolution foreground-background segmentation incorporating a bilateral filtering of the object boundary based on 2D/3D-images is presented in [CTPD08]. ToF cameras can allow for true 3D segmentation, possibly combined with 3D object insertion for live online Augmented Reality [Tho06, IY01] or Shape-from-Silhouette reconstruction [GLA\*08b].

Guan et.al. [GFP08] present a system that combines multiple ToF cameras with a set of video cameras to simultaneously reconstruct dynamic 3D objects with Shape-from-Silhouettes and range data. Up to four ToF cameras are illu-



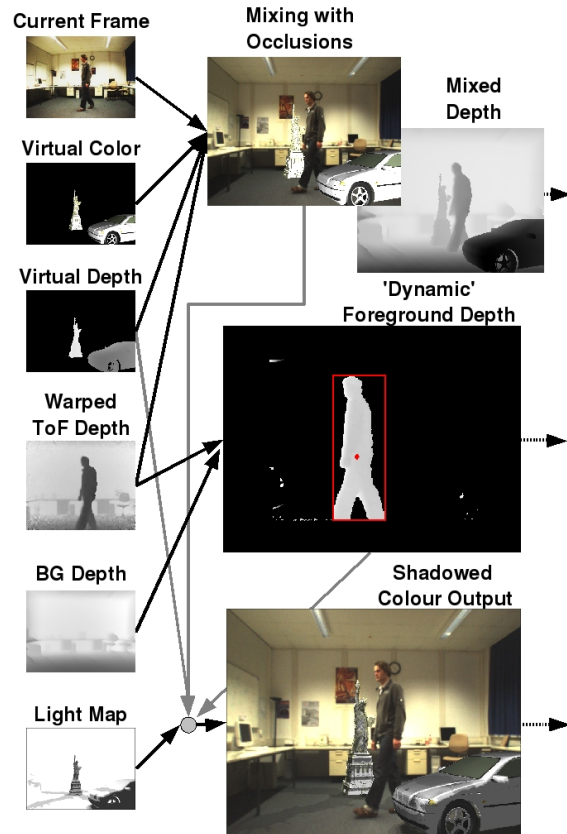
minating the scene from wide baseline views at slightly different modulation frequencies, interleaved with color cameras for silhouette extraction. They extract dynamic 3D object volumes from the probability distribution of the object occupancy grid over time.

In [BSBK08], a Mixed Reality system using a combined color and ToF-Camera rig is discussed. The overview of the system is given in Fig. 7. The key features in this system are the dynamic 3D depth keying and the mixing of real and virtual content. A ToF camera mounted on a pan-tilt unit (Fig. 6) allows to rapidly scan the 3D studio background in advance, generating a panoramic 3D environment of the 3D studio background. Fig. 8, column (1), shows the texture and depth of a sample background scene. The scan was generated with a SR3000, automatically scanning a  $180^\circ \times 120^\circ$  (horizontal  $\times$  vertical) hemisphere, the corresponding color was captured using a fish-eye camera with the same field-of-view. The depth of foreground objects can be captured dynamically with the ToF camera and allows a depth segmentation between the generated background model and the foreground object, providing the possibility of full visual interaction of the person with 3D virtual objects in the room. Fig. 8, columns (2) and (3) show the online-phase, where a moving person is captured both in color (2) and depth (3). Thus a full 3D representation of both environment and person is available in the online phase.

Depth keying and seamless mixing of real and virtual content is now possible. Fig. 9 shows the different steps of the process. The real object can be extracted from the real scene by depth background subtraction using warped ToF depth and background depth. A result is shown in Fig. 9 in the center. Virtual objects will then be inserted at the correct position and with correct occlusion automatically, since a depth map of real and virtual content is available. Finally, even correct light, shading and shadows can be computed if the position and characteristics of the light sources are known [SBK\*08a]. A shadow-map [Wil78] is computed by projecting shadows of the virtual objects onto the reconstructed real environment, and a simple color attenuation is used to render shadows from multiple real light source positions in real-time directly on the GPU. See Fig. 9 bottom for results. Since the ToF camera captures the dynamic object as depth map on the fly, a unified mesh representation of all scene parts – environment, real person, virtual objects – can be constructed, allowing even to cast shadows from the virtual objects onto the real person and vice versa.

## 8. User Interaction and User Tracking

An important application area for ToF sensors is that of interactive systems such as alternative input devices, games, animated avatars etc. An early demonstrator realized a large virtual interactive screen where a ToF camera tracks the hand and thereby allows for touch-free interaction [OBL\*05].



**Figure 9:** Overview of the color mixing and shadowing casting of real and virtual objects on the GPU. On the left hand side all the input images are displayed. Based on the different depth images mutual occlusions can be handled in the augmentation. Moreover foreground segmented depth images and mixed depth images are delivered. The scaling of the augmented image via the light map yields the final color image output (from [SBK\*08a]).

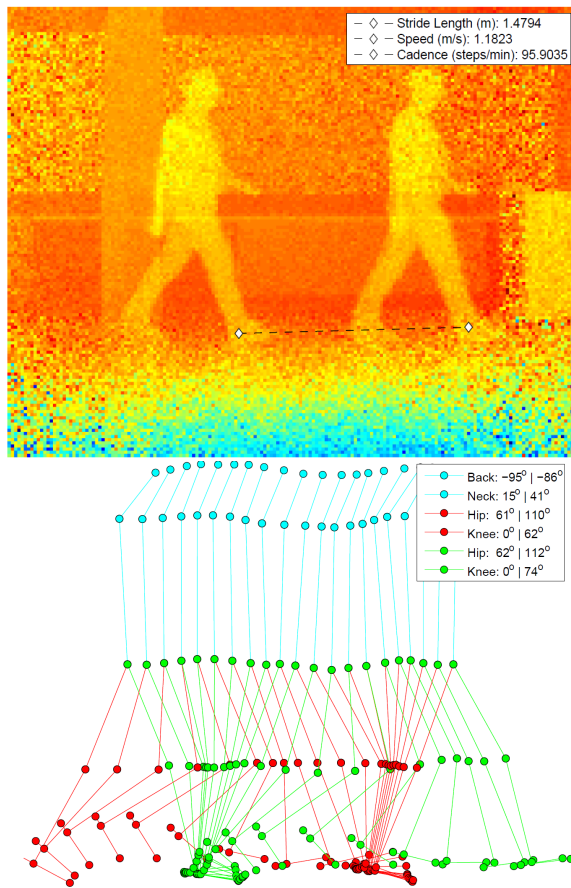
[SPH08b] present a similar application for a touch-free navigation in a 3D medical visualization.

The “nose mouse” [HBMB07] tracks the position of the nose in the camera image and uses this to control Dasher [WM02], an alternative text-input tool, allowing hands-free text input with a speed of 12 words per minute. The tracker is based on geometric features that are related to the intrinsic dimensionality of multidimensional signals. These features can be used to determine the position of the nose in the image robustly using a very simple bounding-box classifier, trained on a set of labelled sample images. Despite its simplicity, the classifier generalizes well to subjects it was not trained on. An important result is that the robustness of the nose tracker could be drastically increased by using both

the intensity and the depth signals of the ToF camera, compared to using either of the signals alone (see Fig. 10). A



**Figure 10:** Left: Example nose-detection results shown on ToF range image; detection error rate is 0,03 [HBMB08a]. Right: The direction the user is pointing in can be computed from the difference vector between the positions of the head and hand [HBMB09].



**Figure 11:** Top: An overlay of two ToF images in a gait sequence. The two image correspond to one stride. Bottom: the articulated human pose model fitted to the ToF gait sequence using a pose-cut algorithm for ToF data [RPL09].

similar approach has been used in [WLL07] to detect faces based on a combination of gray-scale and depth information from a ToF camera. Additionally, active contours are used for head segmentation.

Human machine interaction during an intervention in the sterile environment of an operation room is becoming an important application due to the increasing incorporation of medical imaging. Available ToF cameras have been successfully used to provide a robust, marker-less, real-time, three-dimensional interaction interface by detecting hand gestures and movements [PSFH08, SPH08b].

Gesture recognition is another important user interaction area, which can clearly benefit from current ToF sensors. First results are presented in [HM08], where only range data are used. Here, motion is detected using band-pass filtered difference range images. [HMF08] extends this to full body gesture recognition using spherical harmonics.

Deictic (pointing) gestures are an important class of gestures. ToF cameras make it possible to measure directly where a user is pointing in space. The pointing direction can be used to determine whether a gesture is made towards the system or other people, and to assign different meanings to the same gesture depending on pointing direction [HBMB09]. In this work, deictic gestures are used to control a slide-show presentation: Pointing to the left or right of the screen and making a “hand flick” gesture switches to the previous or next slide. A “virtual laser pointer” is displayed when the user points at the screen. Fig. 10 shows an example detection of a deictic gesture.

Furthermore, the fitting of articulated human models have also been reported. In [ZDF08] a set of upper body feature points are tracked over time in a ToF image data stream, and an articulated human model is subsequently used for estimating the pose of the body parts in a closed loop tracking control algorithm. Moreover, the model provides a feedback to the feature detection in order to resolve ambiguities or to provide estimates of undetected features. Based on a simple kinematic model, constraints such as joint limit avoidance, and self penetration avoidance are implemented.

In [RPL09] a foot-leg-torso articulated model is fitted to a ToF image stream for gait analysis using the so-called pose-cut algorithm [KRBT08]. Here the segmentation and pose problem is formulated as the minimization of cost function based on a Conditional Random Field (CRF). This has the advantage that all information in the image (edges, background and foreground appearances), as well as the prior information on the shape and pose of the subject can be combined and used in a Bayesian framework. In Fig. 11 an example of the fit of a human articulated model to a gait sequence of ToF data is shown (from [RPL09]).

Recent work considers the application of ToF sensors for user tracking and human machine interaction. Tracking people in a smart room, i.e. multi-modal environments where

the audible and visible actions of people inside the rooms are recorded and analyzed automatically, can benefit from the usage of ToF sensors [GLA\*08b]. The described approach comprises one ToF- and six RGB-sensors. A refined shape-from-silhouette technique, based on an initial binary foreground segmentation for RGB- and range data, is used to construct the visual hulls for the people to be tracked. Another different tracking approach has been discussed in [HHK\*08]. Here, only one ToF sensor is used observing a scene at an oblique angle. Segmented 3D data of non-background clusters are projected onto a plane, i.e. the floor, and are approximated by ellipses. Due to occlusion, the tracking involves merging and elimination of individual clusters.

The estimation of range flow can facilitate the robust interpretation of complex gestures. In [SJB02] the authors propose methods that estimate range flow from both range and intensity data. These methods are of particular value for ToF camera applications because ToF cameras provide both types of data simultaneously and in a perfectly registered fashion.

The incorporation of ToF sensors in a mobile robot system has been studied in [SBSS08]. The goal was to setup an environment model and to localize human interaction partners in this environment. This is achieved by tracking 3D points using an optical flow approach and a weak object model with a cylindrical shape. In [GLA\*08a] a system to control an industry robot by gestures is described. The system incorporates a monocular 2D/3D sensor [LHLW07]. The range image is used for a first hand segmentation, followed by a fusion with the 2D color information. The posture classification uses a learning based techniques.

## 9. Light Fields

light field techniques focus on the representation and reconstruction of the so-called *plenoptic function*, which describes the intensity of all light-rays at any point in 3D. Thus, light fields are capable of describing complex lighting and material attributes from a set of input images without a tedious reconstruction of geometry and material properties [ZC03]. Image synthesis based on light fields incorporates interpolation techniques applied to spatially neighboring rays. If these neighboring rays do not correspond to neighboring object points, ghosting artifacts arise, which can only be resolved by using a dense sampling of the plenoptic function, thus requiring a large number of input images [CTCS00].

Other approaches represent light fields with additional geometric information, e.g. a coarse polygonal model [GGSC96]. In general, this requires pre-knowledge or exhaustive geometry extraction in a pre-processing step. Alternative techniques have been introduced based on range maps, yielding an interleaved *RGBz* light field representation [TRSKK08]. The light field samples are arranged in a

spherical manner, thereby guaranteeing a uniform light field representation. This approach provides a more efficient and accurate means for image synthesis, since the correspondence problem can be solved directly using a ray-casting technique. Thus, ghosting artifacts are minimized. Additionally, this light field representation and rendering technique has been extended with progressive data transfer and level of detail techniques [TRSBK08] and it has been applied to interactive high-quality rendering in various application areas [RSTK08].

ToF cameras can be used to acquire *RGBz* light field samples of real objects in a natural way. An additional benefit results from the immediate visual feedback due to the direct incorporation of new data into the light field representation without any pre-calculation of depth information. However, the stated challenges of the ToF cameras, especially the problems at object silhouettes, severely interfere with the required high-quality object representation and image synthesis for synthetic views.

In [TLRS\*08] a system has been proposed that uses *RGBz* light fields for object recognition based on a analysis-by-synthesis approach. A current research setup described in [TRSKK08] includes a binocular acquisition system using a ToF camera in combination with adequate data processing in order to suppress artifacts at object silhouettes (see Fig. 12). Furthermore, this approach includes the re-binning of light field samples into the regular spherical light field representation, eliminating the requirement to locate the sensor at a pre-defined camera positions on the sphere.

## 10. Conclusion and Future Development

In this report we have presented a review of the ongoing research on novel real-time range-sensing devices based on the Time-of-Flight (ToF) principle. These sensors are currently under development, and first commercial cameras are available. ToF cameras based on intensity modulation deliver information about range, amplitude and intensity. Range is derived from the phase shift between the emitted and the reflected light, the amplitude values describe the amount of correlation between the two, and the intensity is related to the amount of incident active light, which is itself determined by the object's distance and reflectivity. An alternative approach is based on optical shutter techniques.

From the applications perspective, these devices exhibit a large number of specific effects that must be considered. Therefore, some space has been devoted to approaches that deal with effects like the systematic and the intensity-based distance errors, with flying pixels caused by depth inhomogeneity and sensor noise. However, not all of these effects can be compensated for. Problems like motion artifacts remain, and model based approaches aimed at reducing the effects of scattering and multiple reflections are still open for further improvements.



**Figure 12:** RGBz light field example from [TRSKK08] using a ToF sensor. A PMD Vision 19k cameras has been used. The artifacts result from the inaccurate depth information at the object boundaries.

A frequently used approach is the combination of ToF sensors with high resolution grayscale or RGB sensors, most often in a binocular setup. This leads to a simple yet efficient multi-modal sensor system that delivers high-resolution intensity and low-resolution range data in real time. The proposed sensor fusion approaches are already quite mature.

A very natural application of ToF sensors is the reconstruction of object geometry, but here ToF sensors deliver rather inaccurate distance measurements compared to, for example, laser range scanners. However, quite a few applications have been realized based on ToF sensors. In particular, depth segmentation of dynamic scenes with respect to a static background has been implemented successfully, enabling mixed reality applications such as the proper integration of real and virtual objects including shadows. There are quite a few open problems in this area of applications. An example is free-viewpoint synthesis, which requires a proper integration of several ToF sensors in real time.

The field of user interaction and user tracking has been widely studied in the last two years, resulting in a number of significant improvements in robustness and functionality based on the incorporation of ToF sensors. This research field has numerous applications in areas where touch-free interaction is required, such as in medical and industrial applications. Depending on the application, the current restrictions of ToF sensors in the range distance can be a limiting factor. However, the proposed multi-modal systems already benefit from the use of these new range sensors, and, in particular, the fusion of range and intensity data has been shown to increase the robustness of tracking algorithms considerably.

First results on the ToF-based acquisition of light fields are at hand. Here, the limited accuracy of ToF sensors still causes severe problems with image synthesis based on light fields acquired from real scenes.

Overall, we are confident that the growing interest in ToF technology, the ongoing development of sensor hardware, and the increasing amount of related research on the algorithmic foundations of real-time range data processing will soon lead to further solutions of the discussed problems, as well as of further problem domains and new applications.

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