# "Flying Triangulation" –
# Acquiring the 360° Topography of the Human Body on the Fly

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## Abstract

We introduce a novel optical measurement principle: "Flying Triangulation". It fills an important gap in 3D metrology because it enables an acquisition of the topography of moving objects. The immunity against relative motion between object and sensor also allows for medical applications. An easy acquisition of complex objects is possible – just by freely hand guiding the sensor around the object. No tracking is necessary. We will present a "Flying Triangulation" sensor for the intraoral measurement of teeth and a sensor realization for the full 360° 3D acquisition of a person's head. Parts of the body can be captured with high precision by comfortably guiding the sensor, with real-time control of the result.

**Keywords:** 3D scanner, freely hand guided, motion robust, tracking free, low cost, intraoral measurement of teeth, human faces and bodies

## 1. Introduction

Acquiring the 3D shape of an object where a motion between sensor and object is unavoidable – such as for an intraoral measurement of teeth – is a difficult task. It is even more difficult when the object has a complex topography – as it is the case for teeth. Most existing optical 3D shape-measuring sensors are based on the fringe projection principle (see, e.g. [3]) which requires a series of at least three camera images in order to generate 3D data. Although precise, the major drawback of this technique is that during the acquisition period the object and the sensor have to stand still. For applications as the intraoral measurement of teeth, however, such a standstill can usually not be guaranteed. Hence, a motion-robust acquisition method is required.

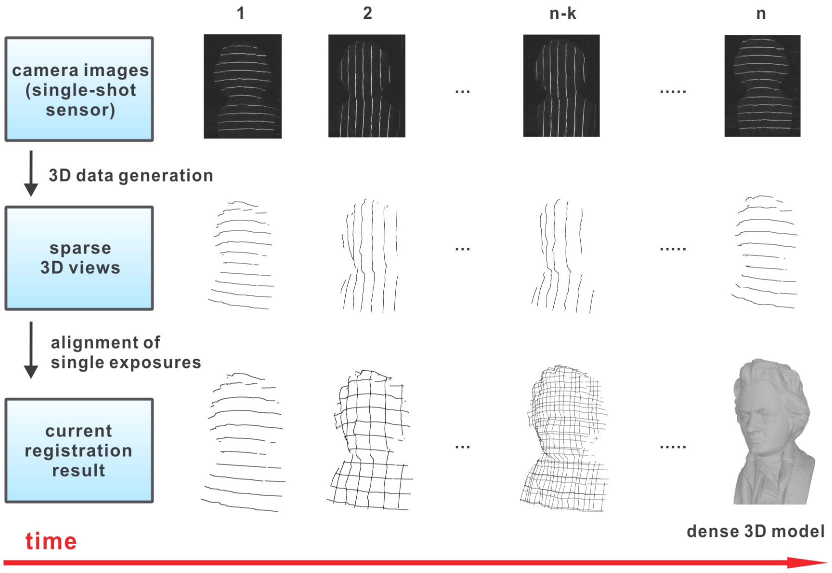

*Fig. 1. Measurement principle of "Flying Triangulation": A single-shot sensor acquires 3D data from each single camera image. The 3D views are aligned "on the fly" and the current result is visualized in real time. When the measurement procedure is completed, a dense 3D model of the object is obtained.*

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Further, because of shading effects, generally the sensor needs to be repositioned to acquire the surface of an object from many different perspectives in order to obtain complete surface information. However, if no real-time feedback is available about the acquisition progress concerning which object parts have been acquired already, a measurement of the complete surface can be a rather elaborate task. Hence, an easy acquisition tool which provides feedback “on the fly” about the already acquired object parts is desired.

## 2. Method

We introduce our novel measurement principle which enables an easy and motion-robust acquisition of the 3D shape of an object: “Flying Triangulation” [1, 2]. It combines a simple sensor with sophisticated algorithms. The resulting sensor can be freely hand guided around the object while acquiring topography information “on the fly”.

### 2.1 Measurement principle

The basic principle is depicted in Figure 1: A single-shot sensor is employed to obtain 3D data from *each single camera image.* This approach guarantees a motion-robust acquisition. The sensor is based on the well-known active triangulation principle: A line pattern is projected onto the surface and observed from a different angle. From the observed pattern the height information can be retrieved. Each resulting 3D view contains sparse 3D data along the observed lines.

A series of such 3D views is captured. In order to obtain a dense 3D model of the object under test the 3D views are aligned to each other already during the sensor movement [5]. This is the crucial part of our measurement principle, since an *automatic* and *robust alignment* of sparse 3D data requires sophisticated registration method. The developed registration algorithms rely on detecting point correspondences in successive 3D views. For this purpose, two orthogonal line patterns are alternatingly projected onto the surface, which guarantees the existence of such correspondences. An important advantage of our approach is that it does not require any kind of tracking device; the alignment is performed by purely using information provided by the acquired 3D data.

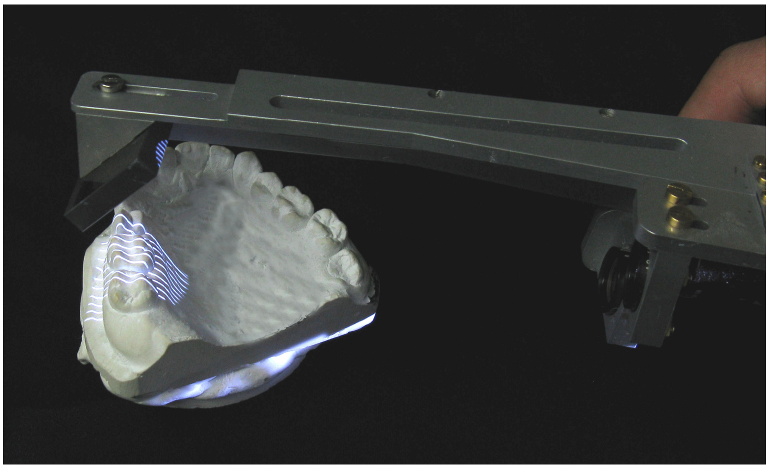

*Fig. 2. The realized sensor for an intraoral measurement of teeth. Depicted is the sensor “in action” while measuring a part of a dental cast.*

Further, in order to efficiently capture the surface the current registration result is visualized in real time. Thus, the user can observe missing areas and will be able to revisit those areas during the acquisition process, so as to fully acquire the entire surface of interest.

### 2.2 Optimization of sensor and algorithms

The components of the sensor were chosen in order to yield minimal measurement uncertainty which is mainly determined by the so-called *speckle noise* [4]. Additionally, the light source, as well as all illumination apertures, the observation aperture, and the patterns were optimized. Further, the registration algorithms were developed in a way to allow for a robust automatic alignment of the acquired 3D data “on the fly”.

## 3. Test/Data

Possible applications of the measurement principle range from an intraoral measurement of teeth to a 3D acquisition of human bodies or even the interior of buildings. We present two sensors which we have researched and developed that are based on the principle described above.

### 3.1 Intraoral sensor

The first sensor is depicted in Figure 2. Its main application is the intraoral measurement of teeth [6].

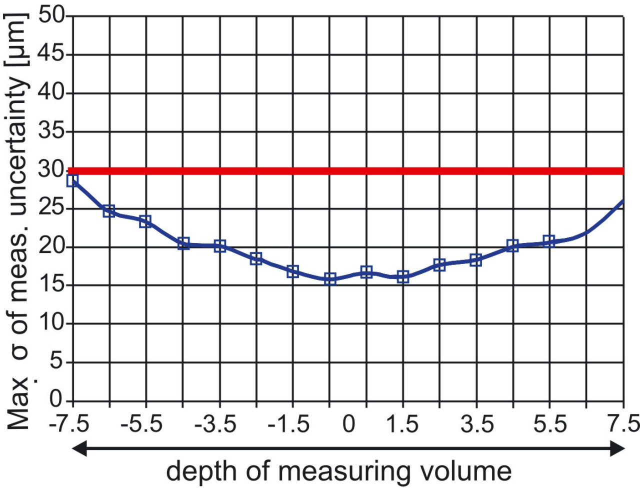

*Fig. 3. Measurement uncertainty of a sensor realized for an intraoral measurement of teeth. The object under test was a sprayed mirror. Within the entire measurement volume of 20 x 15 x 15 mm$^3$ the uncertainty is less than 30 μm for a single 3D view.*

With a frame rate of 30 fps the dental surface can be captured. The exposure time of a single camera image is 15 ms. This time window is short enough to reduce motion blurring to a minimum during the acquisition. Within the entire measurement volume of 20 x 15 x 15 mm$^3$ we achieve a measurement uncertainty of less than 30 μm for a single 3D view (see Figure 3). The object under test was a sprayed mirror.

*Fig. 4. The realized sensor for a full 360° 3D acquisition of a person's head. Depicted is the sensor "in action". The sensor is freely hand guided around the object while capturing 3D data "on the fly".*

### 3.2 Face sensor

Further, we researched and developed a sensor for the full 360° 3D acquisition of a person's head [7]. As mentioned above, the sensor enables a comfortable capturing of parts of the human body by comfortably guiding the sensor around the object, with real-time control of the result. A first realization of the sensor is depicted in Figure 4.

With a frame rate of 30 fps the human head can be captured. The exposure time of a single camera image is 30 ms. Within the entire measurement volume of 150 x 200 x 100 mm$^3$ we achieve a measurement uncertainty of less than 125 µm for a single 3D view (see Figure 5). The object under test was a planar surface.

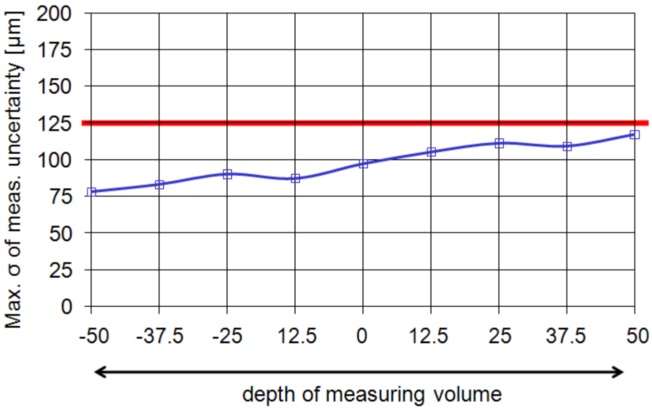

*Fig. 5. Measurement uncertainty of a sensor realized for a 360° acquisition of a human head. Object under test was a planar surface. Within the entire measurement volume of 150 x 200 x 100 mm$^3$ the uncertainty is less than 125 µm for a single 3D view.*

## 4. Results

We now present two measurement examples in the medical field. The first example employs the sensor for the intraoral acquisition of teeth. The object under test is a dental cast. While freely hand guiding the sensor over the cast we acquired the teeth marked by the rectangular box in Figure 6, left.

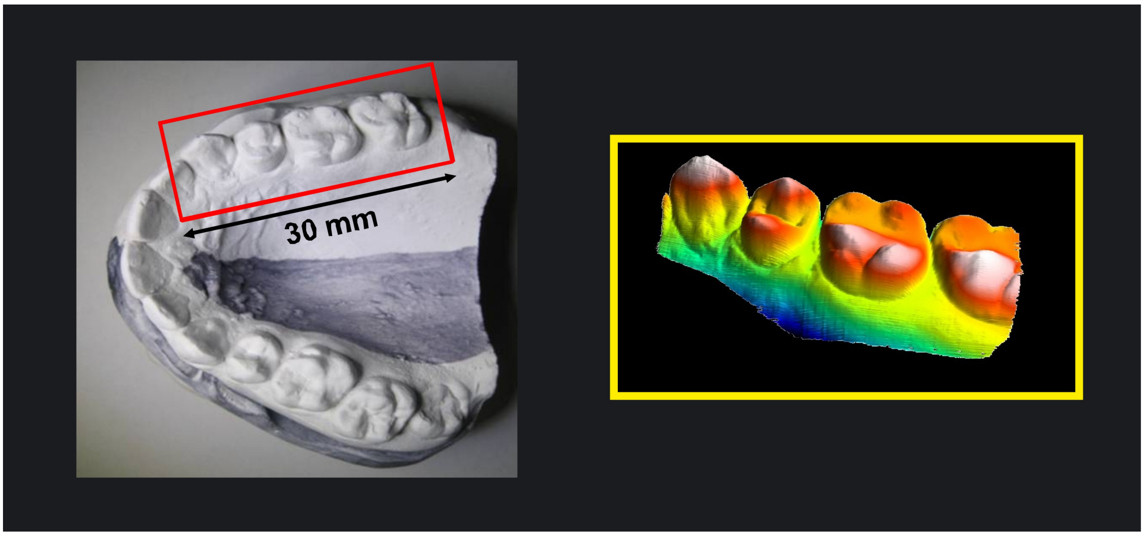

*Fig. 6. Measurement example employing the intraoral sensor. Left: The object under test is a dental cast. Right: The resulting 3D model of the measured part of the dental cast.*

The acquisition time was 15 seconds. In this time window we acquired 500 three-dimensional profiles which were automatically aligned as described above. The resulting three-dimensional point cloud depicted in Figure 6, right, consists of about 3 million points.

The second measurement example employs the sensor for the acquisition of a human head. The object under test is one of the authors head. While freely hand guiding the sensor around the head we acquired the face of the person depicted in Figure 4.

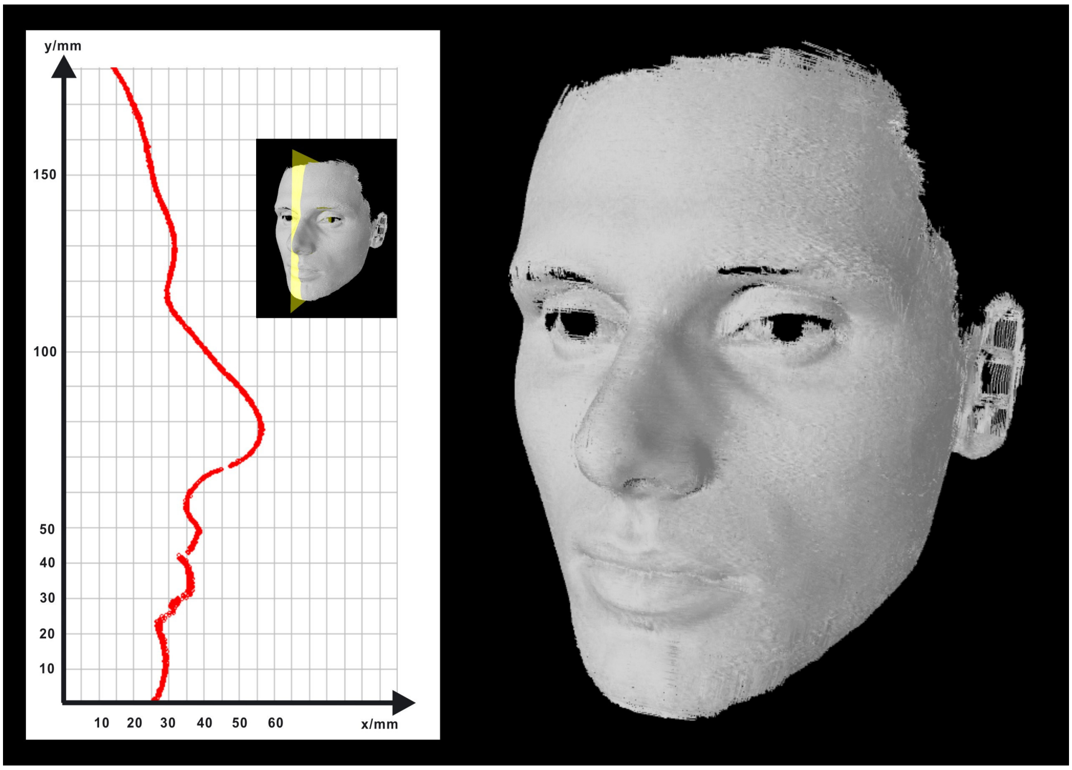

*Fig. 7. Measurement example employing the face sensor. Right: The resulting 3D shape of the person's head. Left: A cross-section of the final dense 3D point cloud.*

The measurement result is given in Figure 7: The right part shows the final dense 3D point cloud of the acquired face. The left part depicts a cross-section and its position through the point cloud.

## 5. Conclusion

We presented our new optical measurement principle "Flying Triangulation" for acquiring the 3D shape of objects. The free hand guidance of the sensor and its motion robustness render it possible for applications in the medical field: Human body parts such as heads or teeth can be measured "on the fly". Because of its high precision and ease of use, this optical 3D measurement principle provides a scanning tool for a large range of applications.

The principle is scalable, covering measurement volumes of some $mm^3$ up to some $m^3$. We presented two realized sensors based on "Flying Triangulation"; one for the intraoral acquisition of teeth and one for the 360° capturing of human heads. Further implementations may include a sensor for the acquisition of complete human bodies or of large rooms.

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