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Flying Triangulation - a Motion-Robust Optical 3D Sensor for the Real-Time Shape Acquisition of Complex Objects

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Abstract. The three-dimensional shape acquisition of objects has become more and more important in the last years. Up to now, there are several well-established methods which already yield impressive results. However, even under quite common conditions like object movement or a complex shaping, most methods become unsatisfying. Thus, the 3D shape acquisition is still a difficult and non-trivial task. We present our measurement principle "Flying Triangulation" which enables a motion-robust 3D acquisition of complex-shaped object surfaces by a freely movable handheld sensor. Since "Flying Triangulation" is scalable, a whole sensor-zoo for different object sizes is presented. Concluding, an overview of current and future fields of investigation is given.

Keywords: 3D Metrology, Optical Sensor, Triangulation, Real Time, Hand Guide.

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INTRODUCTION

The three-dimensional acquisition of object shapes is of increasing importance because of its benefits compared to conventional 2D image-processing. A 3D image is invariant against a large number of effects that disturb the outcome of a 2D measurement [1]. Rotation, translation, illumination or contamination of the object are only some of them. Thus, many industrial sectors like quality inspection, object documentation or the medicine sector have a rising interest in 3D images. This leads to the development of a huge number of 3D sensors in the last years. Several of these sensors are already available on the market and some of them are able to acquire high-quality 3D images [2, 3].

A very common and well-known approach is the fringe-projection method [2]: a sequence of sinusoidal fringe patterns is projected onto the object under test. For each pattern, an exposure is taken with a camera mounted at a fixed angle. From this stack of exposures, the 3D data of the illuminated object surface is calculated. Due to information-theoretical reasons, the 3D data generation from one single camera exposure (single-shot) is not possible with this method, except the object bandwidth is limited [4] or another modality like polarization or color is introduced [5].

If the measured object has a complex shaping, sensor and object have to be re-positioned several times in order to measure the whole object surface. Commonly, re-positioning takes a lot of time and requires an alignment of the single 3D views afterwards. But the fringe-projection method has a drawback which is even more severe for our purpose: due to its multi-shot modality, no relative movement between sensor and object is allowed during the acquisition of the exposure stack. Therefore, it is information theoretically not capable to measure moving objects. Nevertheless, a few multi-shot methods exist which are able to provide good results when measuring moving objects [6, 7]. Usually, this is associated with huge technical effort (cameras with high framerates, high-end illumination systems), which is also connected with high costs.

In our opinion a measurement principle is desired that overcomes these severe drawbacks. The sensor should be hand guided and provide real-time feedback in order to simplify the acquisition of complex shapes for the user. Further, the desired sensor should be motion robust so that a fluent guidance of the sensor around the object (no stop-and-go) as well as the measurement of moving objects is possible. To define the position of the sensor in space, external tracking systems should be avoided. The sensor should be scalable, as inexpensive as possible, and have a wide spread range of application.

"Flying Triangulation" (FlyTri) is a principle that is able to fulfill all these points mentioned above [8]. In order to get a freely hand-guided and motion-robust 3D scanner, a single-shot method is chosen for the 3D data generation. To fulfill the remaining desired characteristics (see Tab. 1), sophisticated algorithms are applied whereas

the sensor itself consists only of simple hardware components in order to save money and be flexible. Thus, the major part of the work load is shifted to the algorithmic side.

TABLE 1. Main characteristics of the measurement principle "Flying Triangulation".

Main characteristics of FlyTri	Means to achieve
Motion robustness	Single-shot method
Hand-guided sensor	
Real-time feedback	Apply sophisticated algorithms and just use simple built sensor
No external tracking	
Scalable	
Inexpensive	
Flexible	

In this paper, we describe the basic principle of FlyTri as well as the crucial steps to register the single 3D views obtained by the single-shot sensor. Second, we introduce the FlyTri sensor family that has been developed due to the scalability of the measurement principle. In the last paragraph, an overview of our current research topics which are very important for the information-theoretical optimization of the sensor principle is given.

BASIC PRINCIPLE OF FLYING TRIANGULATION

Flying Triangulation is based on the well-known principle of active triangulation or light sectioning (see Fig. 1). Light sectioning is a single-shot method. Real 3D surface data can be obtained from one single camera exposure. For an application in a handheld 3D scanner, this is a big advantage. But the light-sectioning method yields also a drawback: 3D data can only be obtained where the light plane intersects the object surface. Therefore, in Flying Triangulation the number of achievable data points is increased by projecting a multiple-line pattern. The projection

FIGURE 1. Principle of light sectioning: The distortion of a projected straight light line onto an object is observed by a camera under the triangulation angle θ . The 3D coordinates of the intersecting surface points can be directly calculated from this distortion in the computer.

of this pattern is done as sharp as possible in order to enable a precise line localization in the camera picture and thus a high accuracy of the measurement result. Because of the desired high accuracy, line encoding methods which could help distinguishing the lines are unwanted. Consequently, only a sparse projection of lines (see Fig. 2.a)) is applied so far in order to ensure a correct line indexing (see last section).

In order to achieve a complete and dense 3D model, the gaps in the sparse 3D views have to be filled. This is automatically done by shifting the sensor, projecting the pattern again and taking a new camera image (see Fig.

FIGURE 2. Projection of line patterns. Each projection step yields only a small number of 3D data points (a). To obtain dense data, the sensor has to be shifted and the projection repeated. Two datasets without corresponding points cannot be registered (b). To solve this problem, two perpendicular patterns are alternately projected (c). This way the existence of corresponding points is guaranteed (d).

2.b)). For the registration of two subsequent sparse views, common surface points ("corresponding points") are required. Generally, the existence of these points cannot be guaranteed (see Fig. 2.b)). To obtain corresponding points independent of the sensor movement we use a trick: Two perpendicular line patterns are alternately projected onto the object surface (see Fig. 2.c)). Thanks to this method, successive views yield enough corresponding points to allow a registration (see Fig. 2.d)). Thus, the FlyTri sensor is equipped with two perpendicularly aligned projection units (see Fig. 3). The internal constitution of the respective projection units varies with the field of application and is described in the next section.

As mentioned above, in order to obtain a dense 3D data set of the object, several sparse 3D views have to be registered [9]. The main task of the registration is to detect corresponding points and map them onto each other. This is done by an iterative-closest-point (ICP) algorithm which is adapted to the nature of the sparse datasets obtained by the single-shot sensor. Since the object is moving relative to the sensor during two subsequent acquisition steps, this is not a trivial task. After a few registration steps, the path of the sensor in space relative to the object can be

FIGURE 3. Schematic setup of a Flying Triangulation sensor consisting of two orthogonal projection units and one camera.

reconstructed, which enables the extrapolation of the next sensor position. This method accelerates the future registration steps and can be used to reduce the registration error as well. We recall that all registration steps are executed without any position information provided by external tracking systems. The information about the position of the sensor in space is obtained only by the registration itself!

After the description of data acquisition and registration in Flying Triangulation above, the workflow of the sensor principle can be explained, which is done in the next subsection.

Workflow of Flying Triangulation

To acquire 3D object surface data with Flying Triangulation, the perpendicular line patterns are subsequently projected onto the object surface. For each projection step, an image is taken with the camera. Since the whole system is calibrated, sparse 3D views can be directly calculated from each single camera exposure. These sparse views are aligned to each other via the registration algorithm. All this is done simultaneously and the current measurement result is displayed in real time on the screen.

The measurement is ready, when the acquired data yield a complete 3D model. For common objects, this takes about five to ten seconds. The resulting model consists of an unsorted dense 3D pointcloud. An example of a 360° measurement with FlyTri can be found in [10].

FIGURE 4. Workflow of Flying Triangulation: From each camera image sparse 3D views are generated (single-shot sensor). The acquired views are registered to each other via the registration algorithm in real time. The current result is displayed as real-time feedback. After a few seconds, a dense 3D model of the object under test is obtained.

FLYING TRIANGULATION SENSOR-ZOO

With Flying Triangulation, a sensor principle for the 3D surface measurement of macroscopic objects is presented which is completely motion robust and avoids any presence of external tracking systems. The surface of complex objects can be acquired within a few seconds and the principle can be nearly free up- or downscaled. Especially the latter property enables the development of differently scaled sensors for various applications.

In Flying Triangulation, all realized sensor setups are optimized to work at their physical limits. In order to achieve the best possible measurement uncertainty in each single 3D view, the major source of noise has to be identified and reduced. In active triangulation, this is the speckle noise [11]. For more details about the optimization see [8].

At the moment, the FlyTri-zoo consists of three 3D sensors with different measurement volumes and a wide range of application (see Fig. 5). One sensor is customized for the intra-oral measurement of human teeth, one for the 3D acquisition of human faces, and one for the measurement of whole human bodies. Of course, other objects with related dimensions and surface properties can be measured as well.

The dental scanner [8] was developed in 2009. It is designed for the intra-oral measurement of human teeth, but is also able to measure similar objects in the mm-range like fingerprints or coarse wafer structures. Even surfaces with high dynamics can be acquired. Each projection unit consists of a simple slide-projector setup and uses a chrome-on-glass mask for pattern generation. As light source, a white-light LED is employed due to speckle reduction. The volume of measurement is about $20 \times 15 \times 15 \text{ mm}^3$ and the absolute measurement uncertainty is below $30 \text{ }\mu\text{m}$ in the whole volume of measurement. With the dental scanner, dense 3D data of a complete dental cast can be acquired via free-hand motion within only 10 seconds.

The face scanner was introduced in 2010 [12]. It is designed for the 3D measurement of medium-sized objects and uses also white-light LEDs for the pattern projection. The measurement uncertainty is below 150 μm in the whole measurement volume of $150 \times 200 \times 100 \text{ mm}^3$. Possible fields of application are reconstructive surgery, 3D face

FIGURE 5. Up to now, the Flying Triangulation sensor family consists of three different scaled sensors for different applications. A wide range of object sizes from approximately 10^{-3} m to 10^1 m is covered. More measurement examples for the respective sensor can be seen in [10].

recognition, orthopedics, pediatrics, art restoration or conservation, forensics, and archeology. The face scanner offers also a texture acquisition. This is done by an additional color camera which is calibrated into the sensor setup [13].

The body scanner, developed in 2011 [14], is designed for the 3D surface acquisition of large-size objects such as human bodies. The data is acquired in a measurement volume of $800 \times 800 \times 550 \text{ mm}^3$ and the measurement uncertainty is below 1.1 mm. The acquisition of color texture is possible. Compared to the other two scanners of the FlyTri sensor family, the body scanner shows one important difference. Since the measurement volume is relatively large, lasers are applied as light sources in order to have an adequate illuminance on the object surface although lasers lead to higher speckle contrast and noise. The lines are generated with a diffractive optical element (DOE). The body scanner supports fields of application which are quite similar to the face scanner. Esthetic surgery, virtual reality, reverse engineering / rapid prototyping, forensics, archeology, and art restoration are some of them.

As it is shown in Fig. 5, the FlyTri sensor zoo covers a wide range of object sizes from approximately 10^{-3} m to 10^1 m . Nevertheless, several requests from industrial and scientific partners reveal that there is a high demand specifically for object sizes settled between the size of face and body. A scanner which covers this range is under construction.

Up to now, each sensor acquires the whole surface of an object under test with the sensor-specific accuracy. In our case, high accuracy means small measurement volumes and hence a slow acquisition process. In order to design this process as efficient as possible, we are working on methods to combine different measurements obtained from different sensors. This would have the advantage that object parts with small surface structures could be measured with a high accuracy by keeping the overall acquisition time small at once.

CURRENT RESEARCH

Although the measurement principle Flying Triangulation yields already good results, the process of measurement is still not as comfortable as desired and easy to handle as it should be. Inexperienced users usually have problems to guide the scanner in a way that all currently measured surface parts are positioned inside the measurement volume. The consequence is occasionally wrong line indexing, caused by ambiguity. Wrong line indexing leads to errors in the 3D data which results in outliers in the acquired 3D model (see Fig. 6). For correct metric data, the phenomenon of wrong line indexing has to be understood and methods to avoid respectively correct it have to be investigated.

Another field of interest is the number of projected lines in Flying Triangulation which is responsible for the 3D data density obtained in one single shot. Up to now, each FlyTri sensor acquires 3D data only along approximately

FIGURE 6. Examples of false indexed data acquired by the dental scanner (a), the face scanner (b) and the body scanner (c).

ten lines which are homogeneously distributed over the field of view. In order to increase the data density and thus decrease the time for acquiring an entire object, the number of projected lines needs to be increased. By the way, the question what the maximal possible density of projected lines is for a single-shot triangulation sensor is not a trivial one [15] and will be an issue of future publications.

In the next subsection, the source of false line indexing will be explained. It will be clarified that false line indexing is the consequence of a deep correlation between the depth of the measurement volume, line density, and triangulation angle. At the end of this section, a short outlook of several approaches to solve the indexing problem will be given.

The Line Indexing Problem

In order to generate correct data with a multi-line triangulation sensor, each line in the camera image has to be indexed correctly. An intuitive approach to this task is to count the lines from the left to the right [16]. But this yields a severe drawback: All projected lines have to be seen in the camera picture at any time. Due to shadowing or weak reflectivity of the object surface, the case that a line or line part is not seen is quite likely. The above mentioned method will fail.

In our approach, each projected line belongs to a unique area on the camera chip. If object points measured always inside the defined measurement volume, each line stays in its own "area of uniqueness". Thus for line indexing, just the areas of uniqueness have to be observed. This method yields unique indexing even if lines are unseen in the camera image. However, a problem occurs if surface parts outside the constructed measurement volume are measured. Here, several line parts will leave their areas of uniqueness and jump to the adjacent areas. False line indexing is the consequence.

The obvious solution of the problem with a small measurement volume is to expand it. Unfortunately, this is not that easy (see Fig. 7): In the standard constellation with small measurement volume, all projected lines remain within their corresponding back-projected areas of uniqueness in space (Fig. 7 a)). The areas of uniqueness for each line onto the camera chip can be seen in Fig. 7 b). If the depth of the measurement volume is expanded, each back-projected area of uniqueness hosts more than one projected line (Fig. 7 c)). Unique indexing cannot be provided. The resulting areas of uniqueness on the camera chip overlap (Fig. 7 f.)). The same problem occurs if the measurement volume is kept constant and the number of projected lines is increased in order to get a higher data density (Fig. 7 d.)) or if a larger triangulation angle is chosen in order to increase the accuracy of the sensor (Fig. 7 e.)).

FIGURE 7. Description of the close relation between depth of the measurement volume, line density and triangulation angle in Flying Triangulation. In the standard constellation (a) all lines on the camera chip remain in their own area of uniqueness (b). If the depth of the measurement volume (c), the line density (d) or the triangulation angle (e) is increased, the areas of uniqueness on the camera chip overlap (f). False line indexing is the consequence.

As it can clearly be seen in Fig. 7, the depth of the measurement volume, the number of projected lines, and the triangulation angle are closely related. These relations are linked across the line indexing problem. In order to increase measurement depth, data density and accuracy at the same time, we are working on several techniques to provide unique indexing. As it is mentioned in the second section, line encoding methods are avoided here in order not to reduce the quality of the measured 3D data.

The first step that we follow in this direction is the detection of wrong line indexing. For this, we already implemented a method that uses the width of the projected lines as indexing criteria: Due to the finite depth of field, false indexed lines can be distinguished from right indexed lines by their width in the camera picture [9]. This simple approach is quite useful for a raw approximation. For detailed index information, other followed approaches are considered to use so far unused information like plausibility assumptions or temporal a spatial context information. Depending on the chosen sensor, a suitable combination of different methods could be selected. Future publications will follow.

CONCLUSION

With Flying Triangulation a sensor principle is introduced which allows the 3D measurement of complex surfaces by freely hand-moving the sensor around the object. The user can see the current result in real time on the screen. All this is done without any external tracking devices. Instead sophisticated algorithms are applied.

Due to its scalability, Flying Triangulation enables multiple scaled sensors for different applications. Dense 3D data with a high accuracy is the outcome of each measurement.

In order to fasten the measurement process and make it easier to handle for inexperienced users, information theoretical relations are investigated which will help to provide unique indexing.

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