How precise is "Flying Triangulation"?

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Flying Triangulation is a novel optical 3D measurement principle. It enables the acquisition of surface information by moving a hand-guided sensor freely around the object while taking a series of sparse 3D views. These partial views are automatically aligned by sophisticated algorithms. No external tracking systems are required. The high precision is exemplarily presented for measurements of faces and teeth.

1 Introduction

Last year we presented our novel optical measurement principle "Flying Triangulation": A single-shot sensor based on active triangulation acquires a series of sparse 3D views while being hand guided around the object under test. Each view only contains 3D data along the projected line pattern. In order to obtain a dense 3D model, all views are automatically aligned to each other. We demonstrated the principal functionality and presented measurement examples [1].

Now we want to answer the question how precise Flying Triangulation is. The accuracy depends on three sources of errors: the physical measuring uncertainty, calibration errors of the single shot measurement, and – especially crucial for our measurement principle – registration errors. We have built two sensors based on our measurement principle. One miniaturized version for the intra-oral measurement of teeth, and one for the measurement of objects like faces or small sculptures (see Fig. 1).

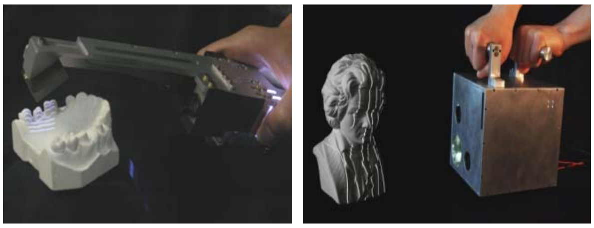

Fig. 1 *Right: Miniaturized sensor for intra-oral measurements. Right: Sensor for measurement of objects like faces and sculptures.*

We first explain how to minimize the measurement uncertainty within each single 3D view. Then, we present efficient and robust algorithms to automatically align an acquired series of hundreds of sparse 3D views and estimate the resulting registration error using data generated by a realistic simulation. Finally, we demonstrate the flexibility of our measurement principle and present a 360° measurement of a sculpture.

2 Precision of single 3D view

As mentioned above, the underlying single-shot sensor is based on active triangulation: 3D data is acquired along a projected line pattern. Since our sensor should be able to measure even inside narrow and deep gaps (e. g. between teeth), we have chosen a small triangulation angle of less than 7 degrees. But this has a drawback: The smaller the triangulation angle, the lower the precision of the sensor. Therefore, the entire optical setup has to work at its physical limits, in order to still reach a measurement uncertainty adequate for the application tasks. Instead of laser, a white-light LED and a lithographic pattern is used to project the lines. This reduces the coherence and the speckle noise. Furthermore, we have optimized the apertures of the setup, in order to find the best tradeoff between depth of field and speckle noise. More detailed information about this topic can be found in [1] and [2].

The achieved measurement uncertainty on a sprayed mirror of a single 3D view for our intraoral sensor is depicted in Fig. 2 (left). Within the entire measurement volume of $20 \times 15 \times 15\,mm^3$ it is below $30\,\mu m$. In Fig. 2 (right) the same is shown for our face sensor, respectively. Here, the measurement uncertainty is below $125\,\mu m$ within a measurement volume of $150 \times 200 \times 100\,mm^3$.

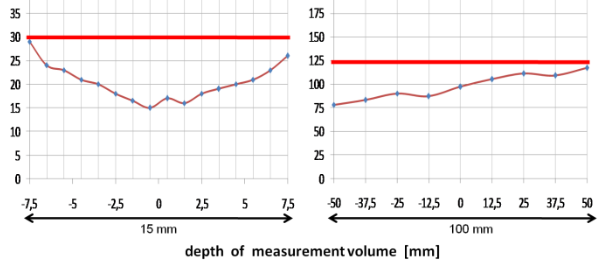

Fig. 2 *Achieved measurement uncertainty within the entire depth of the measurement volume. For the intra-oral sensor it is below 30 µm (left). For the face sensor it is below 125 µm (right).*

3 Precision of registration algorithms

Since we acquire 3D data only along the projected lines within each single 3D view, we use a trick to enable a robust and precise registration: We alternately project vertical and horizontal line pattern. This way we guarantee the existence of corresponding points in consecutive views. Our specially developed registration algorithms find these corresponding points and map them onto each other. Outlier detection and correction methods are used to further reduce the error propagation over the entire series of 3D views. The current registration result is visualized in real time and gives the operator live feedback of the measurement process.

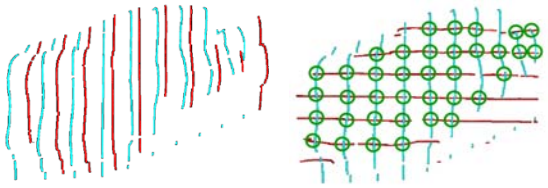

Fig. 3 *Left: If consecutive images contain only vertical lines, no or only few common points may exist. Right: If the orientation of the lines changes as depicted, existence of common points is guaranteed (right).*

To investigate the precision of our registration algorithms we first simulate an acquisition of a series of sparse 3D views along a freely defined sensor path using a 3D model of a dental case (see Fig. 4 left). Then we add noise extracted from real measurements of our intraoral sensor to the generated data and apply the registration algorithms (Fig. 4 right). Since we know the position of the virtual sensor at all times, we can compare the ideal point cloud with the registration result point by point. Tab. 1 displays some statistical information. The pure registration error (10 µm) is clearly below the achieved measurement uncertainty within a single 3D view (30 µm).

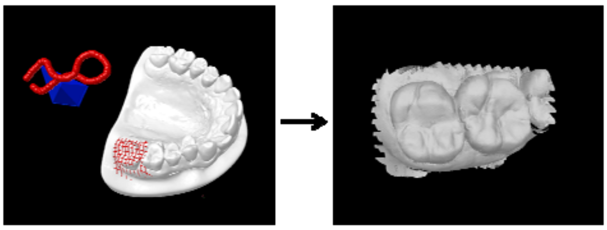

Fig. 4 *Left: Simulated acquisition of a series of sparse 3D views along a freely defined sensor path (red curve). Right: Resulting point cloud after registration.*

Measuring field	2 teeth, 30 mm
Acquired single views	330
Acquired points	2.4 millions
Average total error (noise included)	25 µm
Average pure registration error (without noise)	10 µm

Tab. 1 *Statistical results registration applied on 3D views acquired by simulation.*

4 Measurement example

We demonstrate the flexibility and ease of use of our face sensor with the help of a 360° measurement of a small sculpture (see Fig. 5 and movie [3]). The sculpture is turned around by hand and the current result is displayed in real time. Fig. 6 shows the final 3D point cloud of the measurement and an intersection through it.

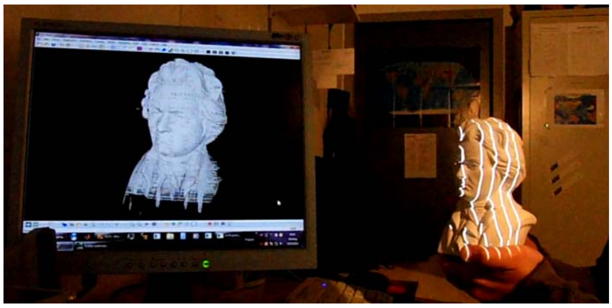

Fig. 5 *360° measurement: Sculpture is turned around freely by hand in front of the sensor. The current registration result is displayed in real time.*

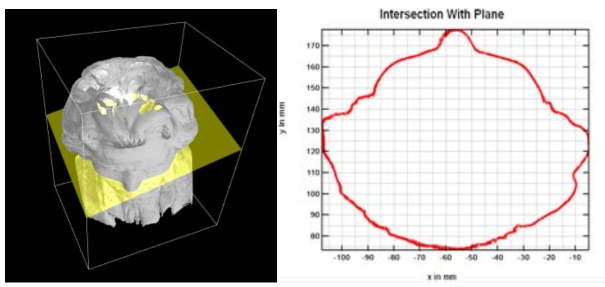

Fig. 6 *Left: Resulting points cloud of 360° measurement of small sculpture. Right: Intersection through point cloud.*

5 Conclusion and outlook

Our measurement principle Flying Triangulation enables the construction of low-cost sensors for easy and flexible measurements of object surfaces. The local precision allows the intraoral measurement of teeth as well as the measurement of faces. The sensor principle is scalable, from measurements of smaller objects like teeth to large objects like entire interior of rooms.

References

[1] [1] S. Ettl *et al.*: „"Flying Triangulation": A motion-robust optical 3D sensor principle," in: Fringe 2009, The 6th International Workshop on Advanced Optical Metrology, W. Osten, M. Kujawinskaja (Hrsg.), Springer, Berlin, 768–771 (2009).

[2] R. G. Dorsch, G. Häusler, J. M. Herrmann: "Laser triangulation: Fundamental uncertainty in distance measurement" in *Applied Optics*, 33(7), 1306-1314 (1994).

[3] Movie of sculpture measurement: *http://www.optik.uni-erlangen.de/osmin/upload/flytri/videos/Messung.wmv*