3D surface scanning, facial features analysis, asymmetry analysis

Agnieszka TOMAKA*, Leszek LUCHOWSKI*, Krzysztof SKABEK*, Michał TARNAWSKI**

3D HEAD SURFACE SCANNING TECHNIQUES FOR ORTHODONTICS

The accuracy of the Minolta 9i 3D laser scanner is evaluated and conditions are defined for its usability in orthodontics. Experiments are described which helped determine optimal scanning conditions such as beam power, patient positioning, the number of scans per examination, and viewpoint selection.

1. INTRODUCTION

The analysis of facial features is a basic examination in orthodontics, performed intuitively by the practitioner during every patient examination. More objective measurements are performed using callipers, or on photographs of the patient [1]. Such measurements are tedious both to patients and doctors, and error prone due to the 2D character of photography.

Since the last decade of the XXth century, means have been developed to digitize 3D shapes. Systems described in [3,4] were either prototypes or mainly used for technical applications. They are, however, in principle, also applicable for orthodontic purposes.

Two basic technologies are available for 3D facial image acquisition: laser scanning and structured light methods [3]. The structured light technology projects lines, grids or other patterns onto an object. The projected pattern is distorted by the shape of the object. This distortion, acquired by a camera, is used to compute 3D points. Laser scanners use a similar principle but the pattern is projected by a laser rather than an image projector. Both technologies yield distance maps. Unfortunately, they are not free from errors and artefacts and their clinical use should be preceded by careful error analysis and planning.

This paper discusses the accuracy of the laser scanner and presents the scanning arrangements and procedures for the purposes of orthodontics measurements.

2. ESTIMATING SCANNER ACURACY

In order to use 3D laser scanner in clinical practice the reliability of scans – their accuracy and repeatability – has to be verified. Such tests were performed for the Minolta Vivid700 3D laser surface scanner in [7] and for Cyberware Head and Face Colour Scanner 3030RGB (Cyberware Monterey,CA) in [8]. Each of these works used a different approach to assess scanner accuracy. The

* Institute of Theoretical and Applied Informatics
** Department of Orthodontics Silesian Academy of Medicine

former used calibrated objects like a cylinder, a dental cast, a plaster facial model. Then the scanned surface parameters are measured and compared with the real values. The latter relied on a statistical evaluation of 3D scans of heads of 5 volunteers scanned at three different times by two different operators. Both studies confirmed that even though there exist some errors due to various factors, both scanners show sufficient precision and repeatability to be used for clinical examination.

The basis of our 3D scanning system is a Minolta VI-9i scanner, and some experiments to confirm the observations and conclusions of the described papers have been carried out.

2.1. PARAMETERS OF 3D SURFACE LASSER SCANNER

The surface scans have been performed using a Minolta VI-9i scanner (fig. 1).

Fig. 1. Minolta VI-9i 3D scanner

The scanner emits a laser beam which is formed into a horizontal stripe through a cylindrical lens, and moved vertically by a rotating mirror. Light reflected from the object is received by a CCD sensor and converted by triangulation into distance data. The process is repeated up to 600 times for changing vertical position of the stripe. The same CCD sensor uses an RGB filter to obtain a colour image of the object when laser light is not emitted.

The data acquisition takes about 2.5 seconds, plus 1.5s for data transmission to the host computer. The scanned surface is registered in the form of a dense mesh with mapped texture. The nominal accuracy of coordinate measurements is 0.05mm in each dimension.

2.2. SINGLE SCAN ACCURACY

2.2.1. PLANE SCANNING EXPERIMENT

In the first experiment the accuracy of scanning planar surfaces was tested. The multiple scans of two planes of the calibration plate was taken from two different views, with different scanning parameters. The deviations between those scans and deviation from the estimated plane were calculated using RapidForm software.

Fig. 2 illustrates the value of the deviation between 5 scans. It can be noticed that the deviation depends on the angle between the plane and the optical axis of the scanner. The deviation also increases with the distance from the scanner. The average deviation of about 0.14mm in this experiment can be regarded as the noise level for scanning plane surfaces.

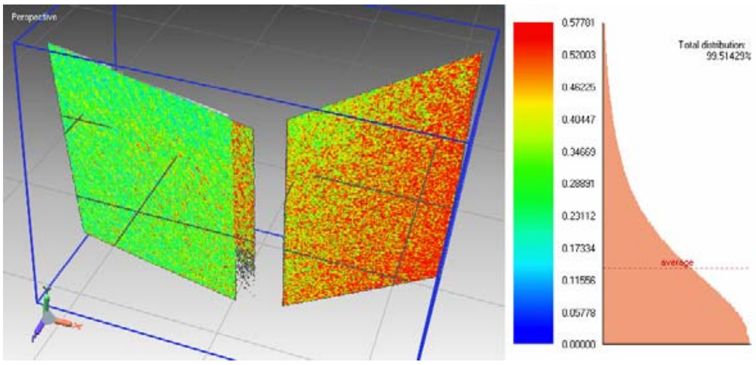

Fig. 2. Shell deviations for scans of planar surfaces

2.2.2. SPHERE SCANNING EXPERIMENT

The next experiment tested the accuracy of scanning a spherical surface. Multiple scans of an 80mm-radius sphere were taken using different scanner parameters. Differences between scans and distances from the ideal sphere were calculated using RapidForm software.

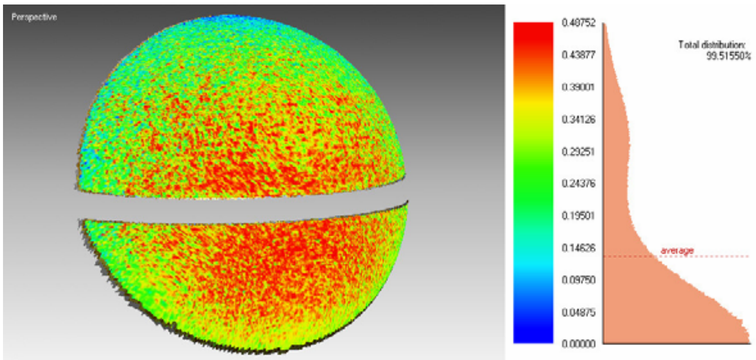

Fig. 3. Shell deviations for scans of a sphere

Fig.3. shows largest error in the center, the optical axis crosses the sphere. It confirms that the scanner is less accurate in the z direction, as stated by the manufacturer and by [7]. This seemingly contradicts the conclusion from our first experiment as to the effect of surface inclination, but the reason for this apparent contradiction is the different scale of the objects. Thus the next observation by [7] is confirmed: small objects, contained in the central part of the scanner's field of view, are scanned more accurately than larger ones that fill most of it.

2.3. SKULL SCANNING EXPERIMENT

In the next experiment three dry skulls (anatomical specimens) were scanned and distances were calculated between localized landmarks which can be localized in one projection. The distances were also measured directly on the skulls with a digital slide calliper (Fig. 5.)

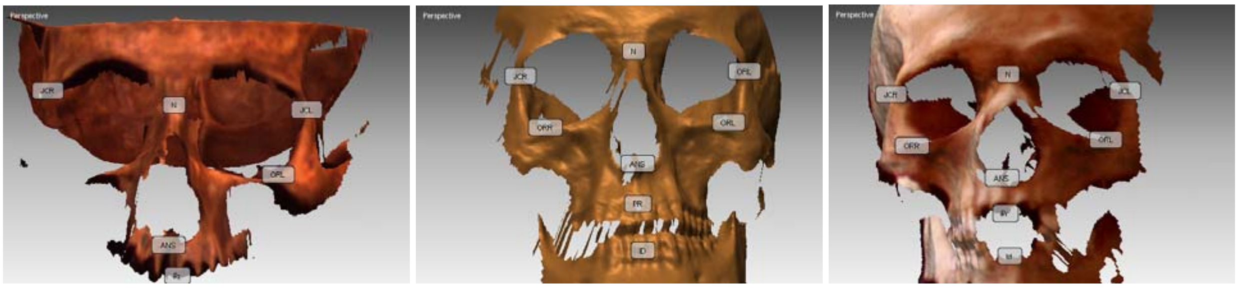

Fig. 4. The anatomic preparations with localized landmarks – single scan study

Mean square differences between the direct measurements on the skulls and single-scan-based measurements is less than 1 mm (0,7 mm for the first, 0,25 for the second and 0,57 for the third skull). Although this experiment does not fully determine scanner accuracy, it allows us to estimate it and decide if the scanner can be used for medical purposes.

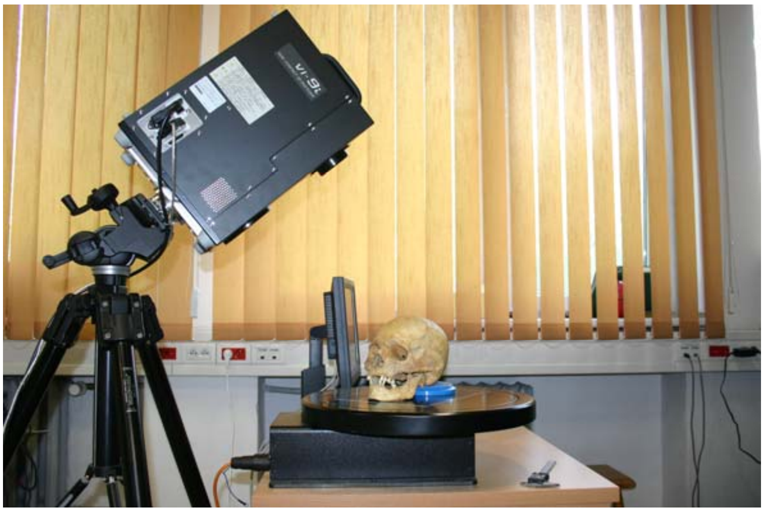

Fig. 5. Scanning a human skull

Although the nominal precision is claimed to be between 0.008 and 0.032mm, we found that the real precision strongly depends on scanning conditions. The noise level is 0,2-0,5 mm depending on the shape of the object. The accuracy of distance measurement is of the order of 1mm, which is acceptable for distances of the order of several millimetres.

3. DESIGNING A SYSTEM FOR 3D HEAD SURFACE SCANNING.

An examination emplacement was created for optimal patient and scanner positioning. A methodology had to be defined to ensure the scanning of all interesting areas. Finally, assumptions are being laid out for a computer system to collect the information in a database.

3.1. PRELIMINARY HEAD SCANNING EXPERIMENT

The next experiment consisted in scanning a human head in order to identify the optimal parameters. Lighting conditions, laser beam energy, noise reduction functions of the scanner, number of scans during a single acquisition, motion, facial surface condition were all tested for their influence on the scan quality.

We found that darker subjects require greater laser energy. Our patients' faces are usually light-coloured and excessive laser energy dazzles the sensor, leading to incomplete scans. Faces have to be scanned with the smallest energy values, but then hair is invisible and strands of hair left loose around the face create artifacts. The use of swimming caps reduces these artifacts significantly. The quality of scans improves when the skin is less shiny. Patient movements, even slight trembling due to breathing, cause considerable loss of scan quality. The number of scans for a single acquisition should therefore be small, to limit discrepancies between scans. Rejecting surfaces inclined less than 20° results in loss of information in non-overlapping areas so this correction is better left for the manual processing stage.

3.2. MEDICAL CONDITIONING

The use of 3D laser surface scanner in clinical practice is subject to some conditions, such as accuracy, repeatability, safety and proper patient positioning.

A laser scanner is a noninvasive device. The only potential concern is the influence of laser light on patient's sight. As the laser is class 2 according to IEC60825-1 its power is low, but staring into the beam is forbidden. While the devices are deemed safe for adults, no safety guidelines exist for children. Therefore their eyes should be closed during scanning.

Patient position is a tradeoff between keeping natural muscle tone, which is best achieved in a natural posture (standing or sitting), and scanning the whole surface of the head, including the underside of the chin and nostrils, which is possible with the head tilted back.

When scans are taken from many viewpoints, the patient should remain motionless for up to a few minutes. He should therefore feel comfortable, lean his head against a headrest to avoid breathing-related movement, and hold his breath during each single scan.

3.3. DETERMINING THE NUMBER OF VIEWPOINTS

The scanner can only scan those surfaces which are visible from a given viewpoint. In order to acquire the entire relevant surface of the head it must move around the patient.

3.3.1. ESTIMATING THE ANGLE OF VISIBILITY

We assume the minimum angle α_b of surface inclination to the optical axis to be 20° (Fig. 6a). In this way we eliminate strongly inclined parts that are subject to greater measurement errors. Given the minimum value of observation angle, it is possible to calculate an observation angle α_{obs}. – in our case approx. 140°, assuming that the angular width Θ of the object is small. Consequently, the minimal number of observation points is 3, assuming that the overlapping region on each side of the single view is close to 10° (Fig. 6b).

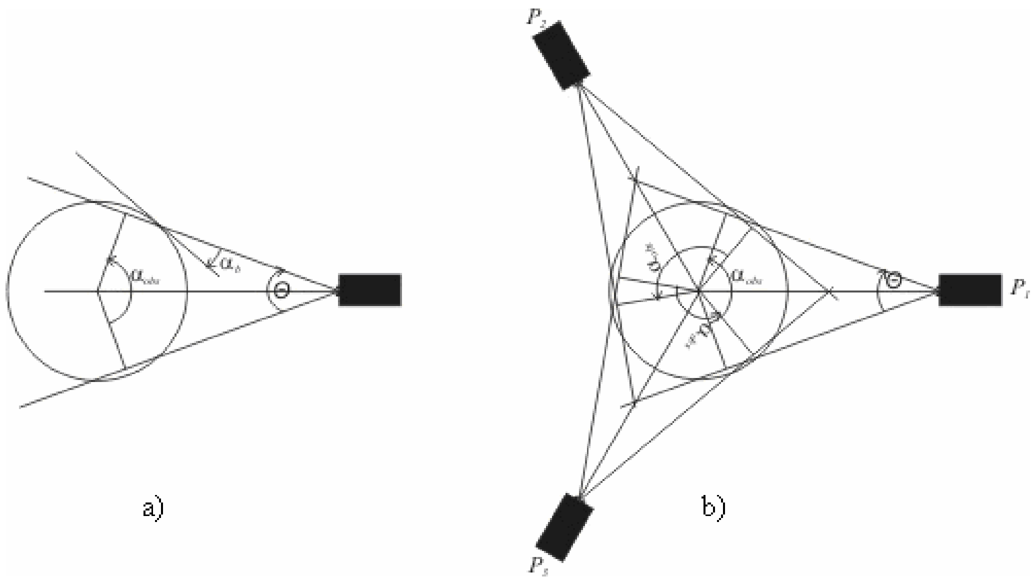

Fig. 6. Angular criteria for the rejection of steep surfaces (distance between object and scanner not to scale)

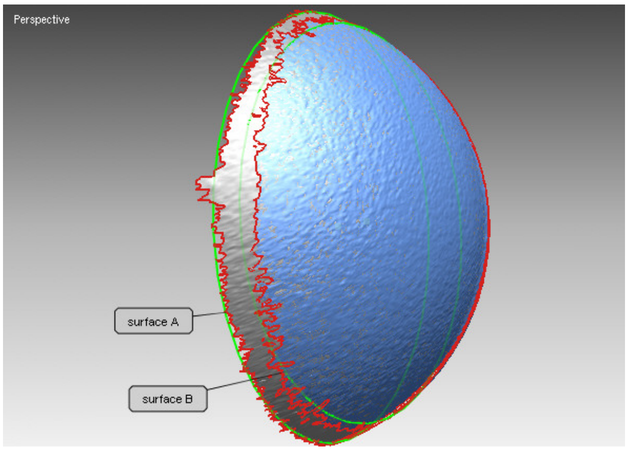

Fig. 7. Comparison of scans of a sphere with rejection of surfaces inclined less then 20° and without rejection

3.3.2. MIRROR AND ROTARY STAGE

There is a number of inconveniences involved in multiple scanning. Merging scans into a single 3D object is very time-consuming if the resulting surfaces are to be seamless. The available software does have automatic merge functionalities, but they are better suited to mechanical parts (easily described by geometric constructs) than to natural forms such as human faces. Moreover, they cannot cope well with objects that change shape, however slightly, between scans, as the human face inevitably does due to breathing and changing facial expression. We have therefore considered using two physical aids to improve the scanning procedure: the mirror and the rotary stage.

Placing a mirror beside the patient would allow us to scan the face from two directions in a single pass. By reflecting both the laser beam and the resulting image to be seen by the scanner's sensor, the mirror creates a virtual object that can, in principle, be scanned just like the real one. Figure 8 shows an attempt to scan two sides of a person's face at a time.

Fig. 8. Scanning a face simultaneously from the right (directly) and from the left (by scanning the “right” cheek of her mirror twin)

Fig. 9. 3D scans obtained with the mirror. Large artifacts protrude from the real person’s chin into the normally empty space in front of her left cheek. Note also the holes and deformities in the face of the “mirror twin”.

The results were discouraging. The mirror part of the scan was visibly inferior in quality. This might be improved by using a precision, front-silvered mirror. But a more fundamental problem occurred in those areas which were visible both directly and in the mirror. In those areas, the scanner was apparently confused by two laser beams appearing simultaneously, and yielded unusable images with severe, spurious artifacts (Fig. 9).

The rotary stage is useful for scanning inanimate objects. Merging scans into a single form is more readily automated if the software can know exactly the rotation axis and angle. For scanning children, the stage proved unusable. When seated on a support that begins to turn, people instinctively turn their heads the opposite way. Most children will not control this reflex. Any restraining device would occlude much of the head and increase patient stress. Moreover, moving the scanner on a wheeled tripod proved faster than rotating the stage.

Another technique is used by the Cyberware family of scanners. In that case, the patient remains seated while a scanning device is rotated around their head in a continuous motion. The device acquires 3D data one vertical line at a time, so there are no large separate images to be merged. The patient’s movements, caused by breathing or changes in facial expression, remain a problem, but it manifests itself in image deformations rather than discontinuities.

3.3.3. SCANNER MOVEMENT TRAJECTORY AND PROCEDURE OF MEASUREMENT

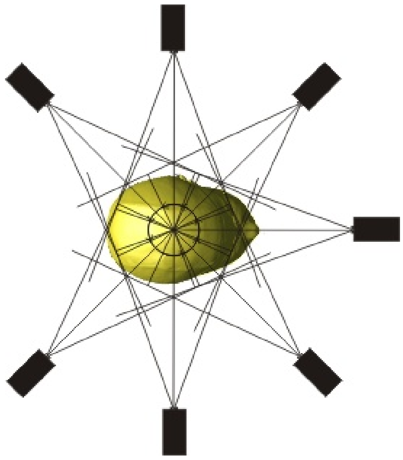

Fig. 10. Chosen set of viewpoints.

Finally we chose 7 observation points, taking into consideration best coverage including reasonable overlap, as well as the layout of relevant anatomical points on the human face. As the first and the most important view we chose the face frontal position.

4. CONCLUSIONS

After the experiments described above, the technique of choice for 3D cephalometric scanning has been defined and the optimal parameters identified. Measurement errors have been estimated for a single scan. Further work should address the problems of scan fusion in order to maximize repeatability and reduce error. When these problems have been solved, it will be possible to assess the total precision of the entire measurement setup [9].

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