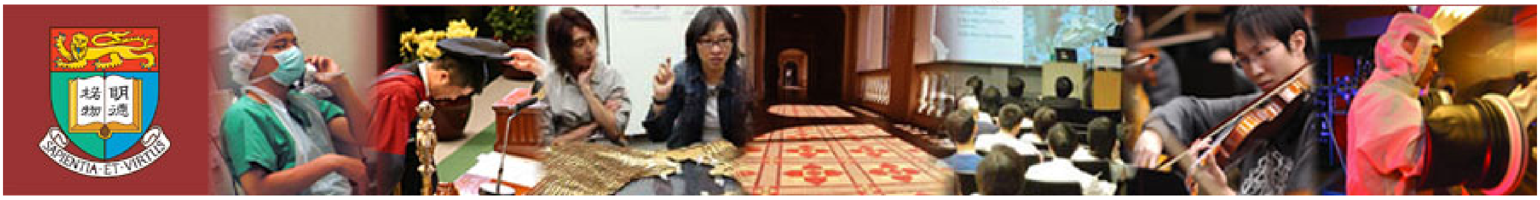

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Recording of natural head position using stereo-photogrammetry: A new technique and reliability study

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Recording of natural head position using stereo-photogrammetry: A new technique and reliability study

Abstract

The purpose of this study was to develop a technique to record physical references and orient digital mesh models to natural head position (NHP) using stereo-photogrammetry (SP). The first step was to record the digital mesh model of a hanging reference board placed at the capturing position of the SP machine. The board was aligned to the true vertical using a plumb bob. It was also aligned with laser plane parallel to the hanging mirror which was located at the center of the machine. Parameter derived from the digital mesh model of the board was then used to adjust the roll, pitch and yaw of the subsequent captures of subjects. This information was valid until the next machine calibration. The board placement was repeatable with standard deviation of less than 0.1 degrees for both pitch and yaw; 0.15 degrees for roll angles.

Keywords

Natural head position; stereo-photogrammetery; level laser; plumbline method

Introduction

Natural head position (NHP) is regarded as a reproducible head position in an upright posture when the subject is focusing at a distant point at eye level [1,2]. Since its introduction in the 1950s, it has been regarded as an essential component in orthodontic and orthognathic diagnosis and surgical planning [3,4,5,6]. Approximation of the NHP in computer environment is traditionally based on anatomical landmarks and planes identified from various imaging modalities ranging from (a) 2-dimensional (2D) radiographs, and (b) 3-dimensional (3D) imaging based on CT scan. Nevertheless, application of this approach is limited in some demanding situations, such as like facial scoliosis and hemifacial microsomia where the existing facial imbalance complicates the identification of planes. Alternatively, the recording can be performed using (i) laser-assisted surface marking during CT image acquisition [7,8,9]; (ii) direct recording of the NHP position using orientation sensors [10,11] (integrated tri-axial accelerometers and magnetometers) from which the readings are applied to re-orient the CT virtual model; (iv) inclinometers[12] and (v) spirit level equipped face bow[13].

Currently, stereo-photogrammetry (SP) machines are readily available for assessment of dentofacial deformity. It provides a non-invasive photo quality 3D capture of object surfaces with high accuracy [14, 15]. As the devices calibration usually does not put any physical reference in consideration; the SP system can only capture the subjects' surface morphology irrespective of anatomical orientation. The resulting 3D facial surfaces are tilted to unknown orientation. Therefore, we need an additional calibration step to correct the orientation. This orientation calibration could be achieved by using some physical references: true vertical and mirror orientation. The aim of this paper is to report a technique to record physical references and its reliability.

Material and Method

In this study, the 3D soft tissue capture was performed using 3dMDface (3dMD USA), which allows reproduction of the 3D coordinates of the same still object in different scans with high repeatability (for each machine calibration). The measured repeatability accuracy[15] for face scanning was found to be 0.016676 and 0.080488mm, respectively for no pose and pose changes. It means that the computed 3D coordinates of the same still object surface will be the same among different scans. This property enables us to capture physical references in a 3D scan. And then capture patients' facial surfaces in another scans. The 3D models of the references appear as we take the facial surfaces with it at the same time. The physical references we suggest to capture are the orientation of the mirror and true vertical which suffice to completely define true orientation.

To allow subjects to make their NHP during image acquisition, a mirror was installed at the center location between the two camera pods and make sure it is vertically placed. A customized reference board, made of a high quality acrylic board, was hung down from a T-shaped holder, which was in turn mounted on a tripod equipped with a 3D head and slider (Figure 1). A 300g plumb-bob was hung at the bottom of the board. A graph paper with vertical and horizontal lines making up a regular grid was taped onto the acrylic board to indicate roll angle. The alignment of the reference board was achieved using a 360° 3-plane leveling and alignment laser (Bosch GLL3-80P, Germany). It had an internal pendulum system such that the laser planes projected, which were made to be perpendicular to each other's (Figure 2), were referring to the true verticals V1, V2 and horizontal H (accuracy ±0.2mm/m, ±0.0115 degrees). The objective is to place the board in the same orientation as the mirror.

(I) Set-up of the reference board

First, the alignment laser was placed in the capturing position (Figure 3a) and was adjusted in such a way that when the laser was turned on, the direct and reflected laser lines from the vertical laser plane V1 showing on the back wall would overlap (Figure 3b). This vertical laser plane V1 was, therefore, perpendicular to the plane of the mirror. The position of the second vertical laser plane V2 (which was perpendicular to the laser plane V1 and was showing on the two side walls) was then marked onto the side walls with two reference lines (Figure 3b), respectively. The plane created by joining these two reference lines was thus parallel to the mirror. The mirror plane was transferred to the capture position. We only need to do this landmarking once unless the mirror is moved.

With the indication of side walls landmarks, we put the alignment laser away from capturing position to the left side (Figure 1) and adjust it to the position that the vertical laser plane V2 points to the mirror plane references. The reference board was then placed at the capture position along this plane. When the board was aligned to facing the mirror, the laser beam creates shadows on the right wall from the threads in which they overlap (Figure 1, right). The size of the board shadow was also minimal. This defines the yaw angle of the board, which is the same as the mirror, in the digital mesh model. For the remaining physical references, the pitch angle of the reference board was kept at true vertical with a plump bob; the roll angle of the reference board was aligned with a level laser at the front side (e.g. at 3D camera rig) beaming on the graph paper grid lines.

3D capture of the reference board was performed when the whole setup was steady and no vibration was noticeable. The data was exported in Wavefront (OBJ) format for correcting the subsequent captures to NHP using MeshLab (Visual Computing Lab, ISTI-CNR) [16].

(II) Alignment of the NHP

The 3D facial surfaces were taken where patients were asked to be relaxed and looking straight into the mirror at their own eyes. The 3D image data was exported in OBJ format and imported to MeshLab for further adjustment. Since the reference board was set to be at the true vertical and facing the NHP alignment mirror with the aid of the laser beams, fitting of the board in both the pitch (x-axis) and yaw (y-axis) can be performed simply by adjusting it back to upright angulation. In using MeshLab, the correction can be done in two steps:

1. Fit the reference board model to XY plane to correct yaw and pitch angulations;
2. Correct roll angle according to the graph paper grid lines of the reference board.

In the first step, the reference board and face models was loaded into MeshLab. The reference board model was selected as active layer. The filter function “Transform: Rotate to fit into a plane” was applied on the reference board model. The option of “Apply to all layers” was also ticked in order to apply the corresponding transformation of the reference board correction to all other face models layers. Secondly, adjust the roll angle of the reference board model in Z axis using the filter function “Transform: Rotate” according to the graph paper texture which indicates the true horizontal/vertical at the frontal view.

The work flow of the proposed method is depicted in Figure 4. The digital mesh model of the reference board is captured at first and recorded (lower left). Then it is superimposed (upper right) with the subject's face models (upper left). The board was corrected to upright angulations using automatic XY plane fitting and roll angle rotation. In the lower right of Figure 4, the reference board model appears as a red thin line showing the true vertical in the profile view. In the frontal view (right), the face model roll angle was corrected along with the reference board according to the graph paper grid lines (small picture) which was aligned with level laser beams.

Accuracy Test

The aim of this test was to test the repeatability of the reference board placement. Following the calibration of 3dMD, the setup, alignment and capture of the reference board were repeated 20 times by one investigator (TCH). In MeshLab, spheres of diameter 20mm were created and superimposed to the reference board. Three patches of 3d vertex points along x- and y- axes were extracted from the intersections of the board mesh models and aligned spheres (Figure 5). They were then used to fit 3D straight lines. Roll, pitch and yaw angles were then calculated from these lines.

Results

20 digital mesh models of the reference board were recorded. Mean and standard deviations of the roll, pitch and yaw angles of the board were calculated from the fitted straight lines from vertical and horizontal vertex patches. The angular deviations of the boards from the means were within ±0.2 degrees (Figure 6), which was considered to be clinically insignificant. Standard deviations were 0.0778, 0.1042 and 0.0780, respectively, for the pitch, roll and yaw angles.

Discussion

Traditional approaches to obtaining NHP require the placement of markers on subjects' face[7,8,9]; using orientation sensors with bite-jig[10,11]; wear eyeglasses mounted with inclinometers[12]; or hold spirit level equipped face bow[13]. When using markers[7,8,9], the procedure of putting marks on patients' face could introduce reproducibility and variability problems. It also lengthens the operation time required for making each of the 3D or CT scans.

When using orientation sensors[10,11], the electronic devices are auto-calibrated, aligned and embedded in a box for mounting on a bite-jig. When capturing 3D photos at NHP, the patient is required to hold the device with the bite-jig. The orientation information is automatically recorded and transferred to the final 3D model of the device chassis; hence the operator variability is minimal. However, this approach consists of some error sources: 1) surface registration of box chassis to the captured faces 3D models; 2) adverse effect on NHP when holding the box; and 3) sensor errors due to improper handling and inhomogeneous magnetic fields in the 3D capturing room. This approach requires more clinical validation.

In the approach of using inclinometers[12], two inclinometers were mounted on eyeglass frame to record pitch and roll angles of the subjects' NHP. The purpose is to make use of the readings and the eyeglass frame shown in the recorded cephalogram to retrieve the NHP. This approach has a merit that the device can keep recording dynamic NHP in any places after took the lateral cephalogram. However, it cannot tell the yaw angle and the achieved method error was 0.6-0.7 degrees (SD 0.9-1.0 degrees). For the approach using face bow[13] to reproduce NHP in articulator for orthognathic surgery planning, traditional orbital pointer is replaced with a spirit level. The horizontal plane reference (which defines pitch and roll angles) is recorded by fixing the spirit level on the face bow when its bubble is centered. When compared to the lateral cephalogram, the measured disagreement of transferring NHP to articulator was -5.2 to 4.2 degrees for 6 subjects tested.

In summary, traditional approaches capture images of physical references along with the subjects in the same scan. In the proposed approach, the capturing of physical references information is only needed when the machine is re-calibrated and they are obtained in separate scans. It does not make any difference to the normal 3D scanning operation. The patient is able to achieve NHP without any devices attached or troublesome markings on the face. More importantly, the proposed approach has a very high repeatability and accuracy. Pitch angle is automatically aligned to the true vertical by using the plump blob. Roll and yaw angles are aligned using the leveling laser. The adopted commercial professional leveling laser has an accuracy of ±0.0115 degrees. It is much more accurate than using some of the high-end miniature size orientation sensors, which typically achieve ±0.7, ±0.7 and ±1.5 degrees of accuracy for pitch, roll and yaw angles, respectively.

Regarding the limitation of capturing NHP information in SP device, it should be noted that the proposed approach works only if the SP device is sufficiently repeatable (without surface registration) and able to scan the reference board. In this study, high overall repeatability of board placement is achieved using 3dMDface. Besides, the field of view limitation of the SP device and reconstruction methods also affects the design of the reference board and the chosen physical references. Currently, the reference board is placed vertically. The reason is that the adopted 3dMDface camera is configured to capture facial surfaces for the subjects in their upright posture. Two camera pods are placed in left and right anterior sides of subject's face covering left to right ears. However, it is not possible to capture a horizontally placed board due to the limited field of view. More camera pods (e.g. setting in 3dMD Cranial) are needed to cover capturing the superior/inferior surface of objects. Validation is needed for other SP devices using other reconstruction methods.

In the current trial, only one alignment laser was used in the two adjustment steps for the yaw and roll angles. This required around 10-15mins for the whole setup, which included time to allow the hanging reference board to become steady. In future studies, more alignment lasers can be used, where they can be mounted onto walls to accelerate the alignment process. This would also further improve the repeatability. Another possible improvement is to add one more leveling laser in front of the board for adjusting the roll angle, while the yaw can be indicated from the side level laser at the same time. For extracting physical reference information from the 3D mesh models of the board for NHP alignment, it is automatic for correcting the yaw and pitch angles by using the "fitting to XY plane" function in MeshLab. Further research on fully automatic correction is under investigation. It can be done by recognizing specially designed texture/shape pattern for indicating the horizontal and vertical axes.

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Figure Legends

fig1.jpg

Figure 1 – The hanging reference board was placed at the capturing position, which was aligned to make it parallel to the mirror using the alignment laser (at the left hand side of the photo). The graph paper on the board indicated the roll angles needed to rotate the digital models back to the true vertical. When the board was aligned to facing the mirror, the laser beam creates shadows (green arrows) on the right wall from the threads in which they overlap. The size of the board shadow was also minimal.

fig2.jpg

Figure 2 – A 360° 3-plane leveling and alignment laser alignment laser is adopted for the alignment. It projects laser beams along 3 planes that are perpendicular to each other: true vertical V1, V2 and horizontal H.

fig3.jpg

Figure 3 – A top view of the 3D capture room. A 360° 3-plane leveling and alignment laser alignment laser is placed in the capturing position of the 3d camera. (a) The projected V1 laser plane on back wall deviates from the reflected V1 laser plane from the mirror. This indicates that the V1 laser plane does not project straight on to the mirror. (b) Adjust the heading of the laser device in that the direct and reflected laser lines showing on the back wall overlaps. Place landmarks on the side walls guided by the V2 laser plane which is perpendicular to V1.

fig4.jpg

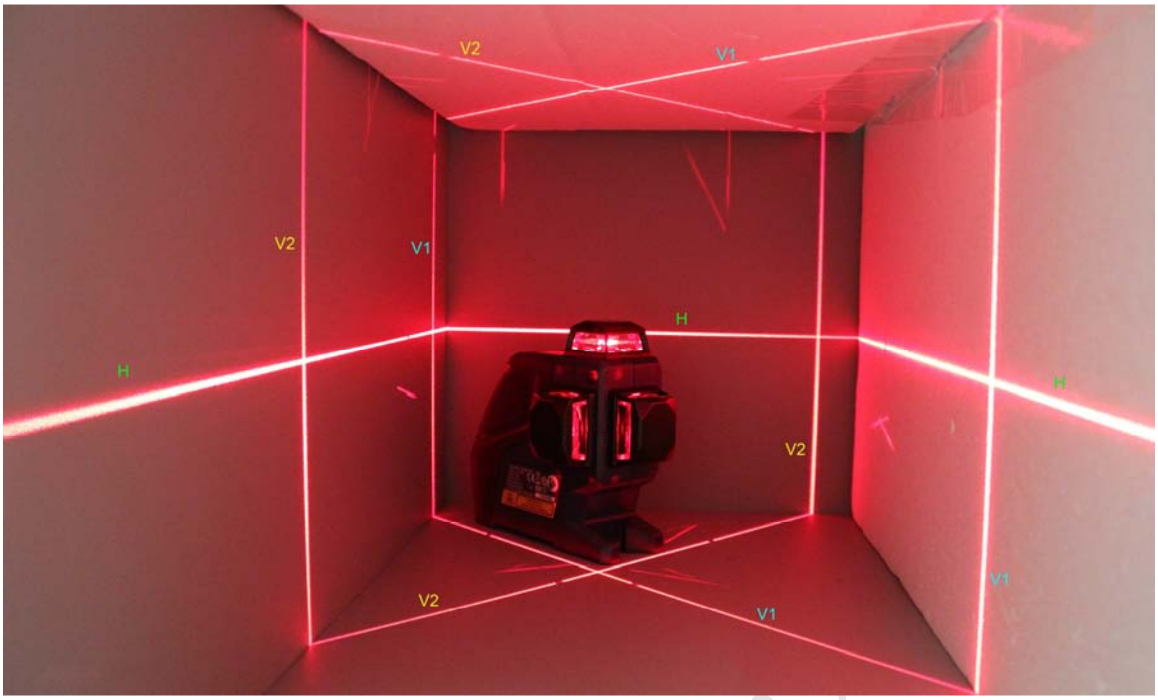
Figure 4 – The digital mesh model of the reference board was first recorded (lower left). It is then superimposed (upper right) with the subject's face model (upper left). Face models were corrected to NHP by using automatic XY plane fitting (correct pitch and yaw at the same time) and roll angle rotation on reference board model. In the face model at profile view (left), we can see the reference board model as a red thin line showing the true vertical. The face model at frontal view (right) is corrected along with the reference board according to the graph paper texture (small figure) which was aligned with level laser beams.

fig5.jpg

Figure 5 - Sphere models were first created in the MeshLab and then superimposed to the center at the graph paper's marks which indicated the horizontal and vertical directions. They were then used to select vertex points by intersecting with the board mesh model. The extracted vertices were then used to fit 3D straight lines (The 2 extreme points in the z-direction were added for better visualization).

fig6.jpg

Figure 6 - The angular deviations of the reference board placement using the proposed approach.



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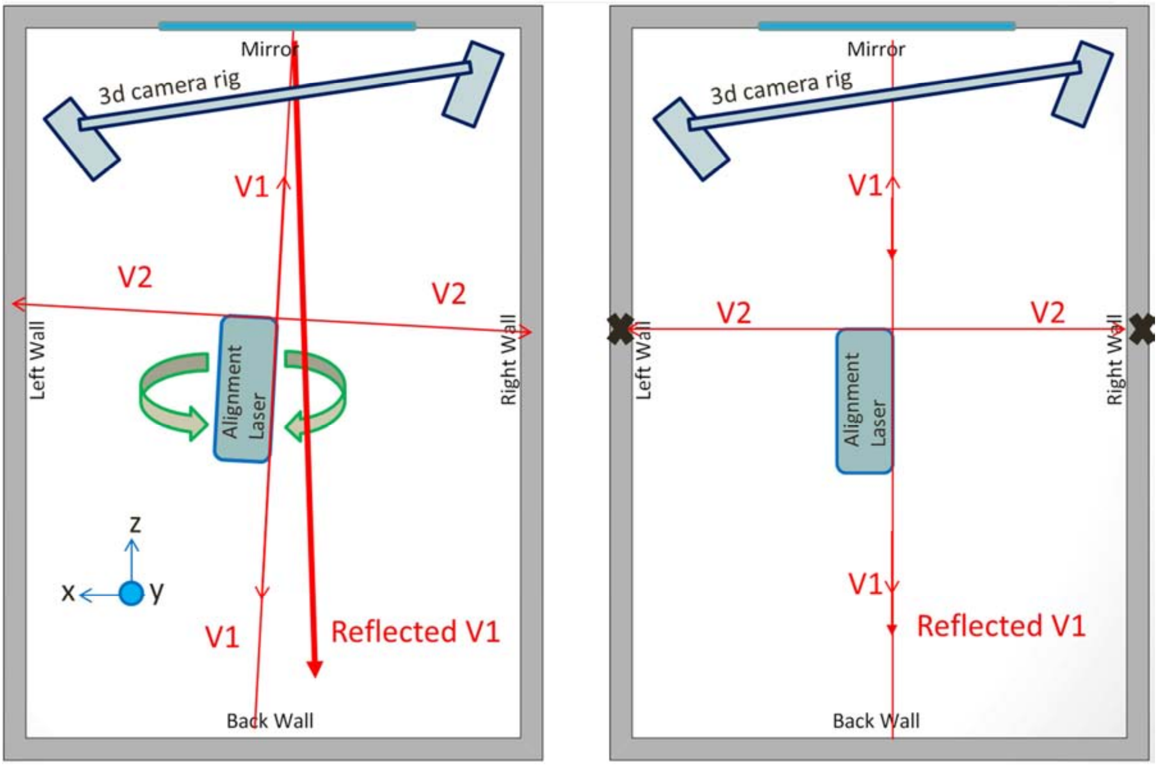
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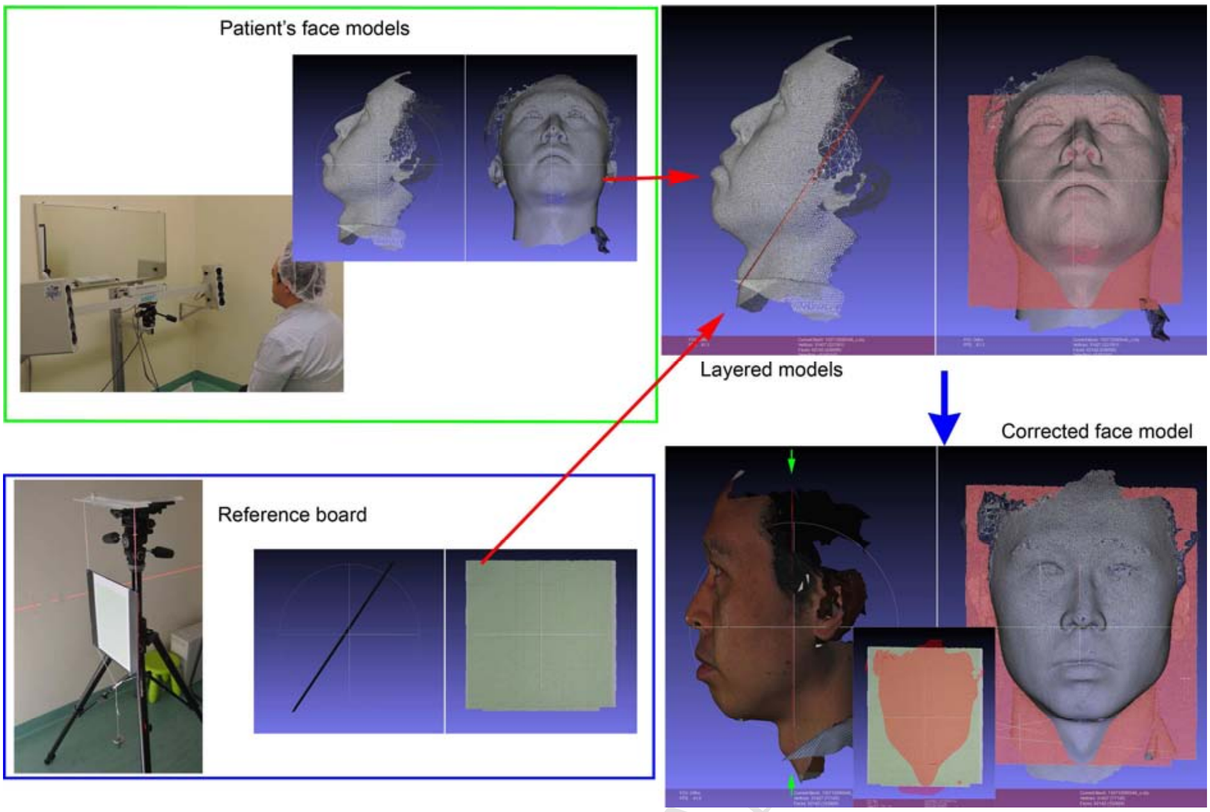
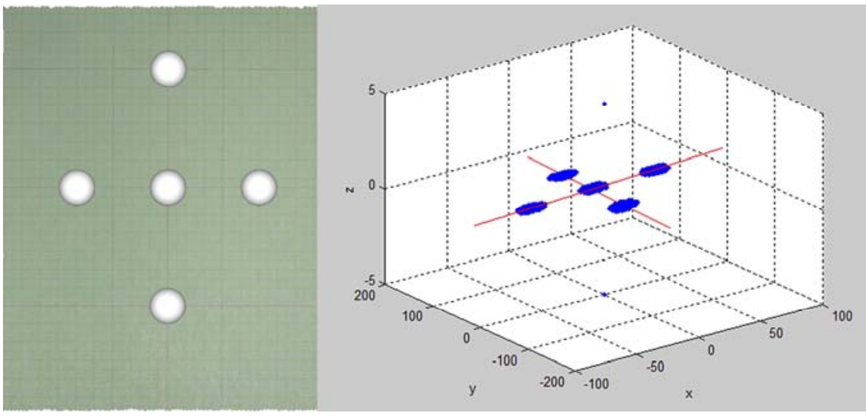


Patient's face models
Layered models
Corrected face model
Reference board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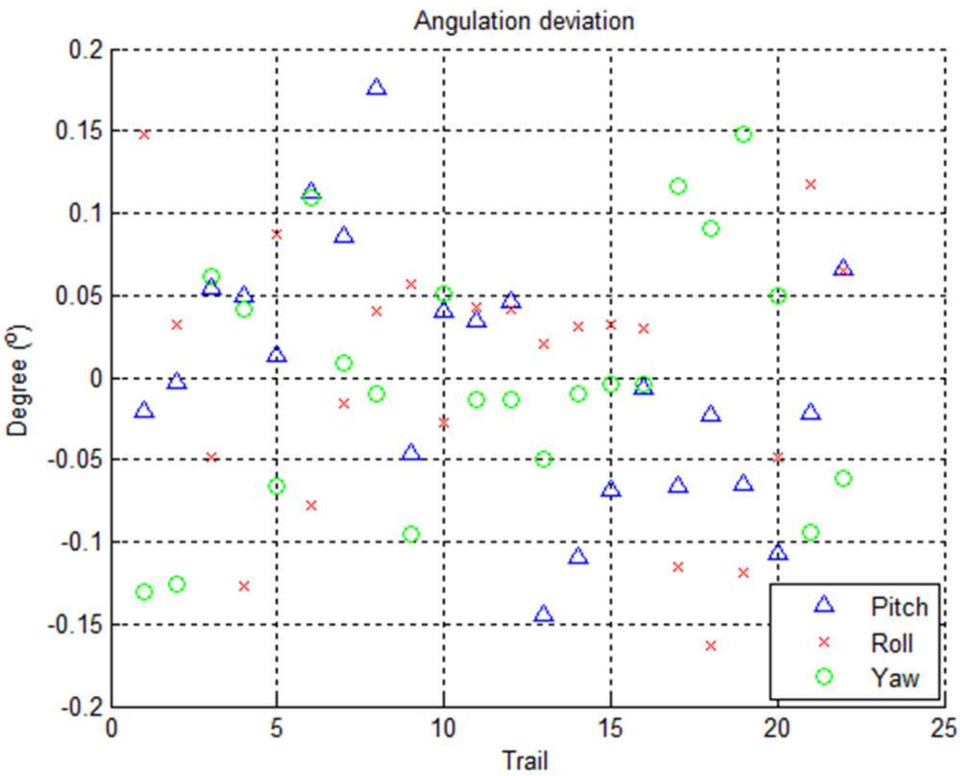
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