4D PHOTOGRAMMETRIC RECORDING OF SOFT AND HARD TISSUES OF THE LOWER PART OF FACE FOR DECISION MAKING IN DENTAL TREATMENT PLANNING

D. Nikolopoulos[b] , V. Tsioukas[c], L. Sechidis[b], P. Koidis[a], P. Patias[b]

[a] A.U.Th., Faculty of Dentistry, Thessaloniki, Greece - pkoidis@dent.auth.gr
[b] A.U.Th., Faculty of Surveying Engineering, Thessaloniki, Greece – (patias, lazikas, dimos) @photo.topo.auth.gr
[c] Demokritos University of Thrace, Dept. of Architectural Engineering, vtsiouka@arch.duth.gr

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ABSTRACT :

Orthodontic prosthetics is dealing with dental deformity problems that may occur in a variety of oral cavity diseases and is trying to fix the aesthetic behavior using appropriate surgical operations or therapies.

Prerequisite to the proper surgery planning and the application of the optimal treatment is the correct documentation of the dental problem, which is currently performed using conventional measuring techniques of questionable precision and accuracy. Especially, the lip line projection on the upper jawbone, which is determining the amount of the gingivas' exposure is a criterion of good aesthetic impression, and should be recorded in the best possible accuracy. Further processing should follow in order to create the detailed diagrams of the lip line in several expression of the mouth, presenting the current dental condition of the normal mouth behavior.

The conventional measuring techniques (using a calibrated ruler or any other device that measures the distance between two district points) that are currently used cannot provide a secure documentation result due to their inability to record the overall 3D object model together with a strictly estimated accuracy.

However, the use of stereoscopic image processing of image stereopairs that have been previously oriented (in terms of the exterior and relative location) can be used to record the projection line of the lip on the upper jawbone. The image stereopairs are recorded in several different mouth attitudes and are relatively compared and interpreted by the specialist doctors.

This paper is describing a research attempt to create an integrated phorogrammetric environment having the highest degree of automation on a series of image stereopairs to extract the geometry of the dental features that provide the problematic situation of a patient's denture.

1. INTRODUCTION AND AIM

An attractive or pleasing smile involves the harmonic interactions among three primary components: lip position, teeth, and associated gingival architecture (Kapagiannidis et al., 2005). The position of the lips during smiling defines the type of the smile (Tjan and Miller, 1984), which influences both clinical and technical procedures required for an aesthetic result of dental prosthetic restorations. The inferior border of upper lip (lip line), as lip moves vertically during smile, affects and determines the amount of tooth display (Lichter et al., 1999). Teeth exposed during smiling are an important part of the anatomy of an aesthetic smile (Mathwes, 1978). As a consequence, variables such as number, size, shape, position and colour of natural or artificial teeth visible during dynamic functions, like smiling and speaking, as well as gingival and supporting bone architecture, must be taken into diagnostic and therapeutic consideration for mouth rehabilitation through the construction of prostheses.

Increased aesthetic demands in dental fixed prosthetic restorations have focused primarily in the anterior teeth region, although many subjects display not only premolars, but also even first and second molars during natural or exaggerated smile (Tjan and Miller, 1984, Dong et al., 1999, Al-Obaida et al., 1995). Premolars are partially visible in over 80% of the smiles, and display more than 65% of their clinical crown length during smile, while gingival display is greater for premolars compared to both central incisors ($p<0.001$) and canines ($p<0.05$) and displayed gingiva is found in first and second premolars in 44% and 49% of subjects, respectively (Kapagiannidis et al., 2005).

The intracrevicular placement of fixed prosthetic restorations margins in anterior tooth region has become a common procedure in clinical practice (Watson and Crispin, 1984), although numerous studies reveal that this can lead to gingival inflammation and attachment loss (Valderhaug and Birkeland, 1976, Lang and Anderhalden, 1983, Reeves, 1991, Valderhaug, 1991, Schatzle et al., 2001). In addition, low percentages of gingival display of maxillary anterior teeth have been reported (Crispin and Watson, 1981). The decision, however, for restorative margin placement is directly related, among other parameters to the amount of gingival display at different functional lip positions such as during speech, exaggerated smile and rest position. The preservation of gingival health in combination to an acceptable appearance of a smile is an important consideration in clinical practice. Thus, it is of clinical interest to investigate the degree of tooth and gingival display in the premolar region, as sufficient data are lacking while aesthetic considerations for this area may be overlooked. The reveal of any possible correlations between tooth and gingival display, gender and age is of interest as they could be used as guidelines to aesthetic considerations in prosthetic restorations of maxillary teeth (Miller, 1989). In many studies female subjects have been shown a tendency to display significantly more gingival tissue than males, (Peck et al., 1992, Acherman and Ackerman, 2002, Owens et al., 2002, Rigsbee et al., 1988), while the ‘gummy smile’ has been reported as a female characteristic (Peck et al., 1992). It has also been reported that in rest position, the display of maxillary central incisors decreases with age and is concurrently accompanied by a gradual increase in the display of mandibular central incisors (Vig and Brundo, 1978, Wassan, 2004).

However, all of these quantitative and qualitative estimations and calculations concerning the aesthetically critical area of the mouth, with the associated lips, teeth and gingiva have been performed either empirical or using plane 2-D imagery. The aim of the present study was the development of an instrument for 3-D visualization and accurate capturing of the geometry and architecture.

2. THE PHOTOGRAMMETRIC APPROACH

The Photogrammetric approach, in general, is based on the exploitation of overlapping images, in order to reconstruct the geometry of scenes.

As mentioned in Mitchell et al., 2002 “Photogrammetric measurement has been used on the face more than on any other part of the body. Measurements have been made to monitor facial shape as it changes over an extended period of time, through growth (e.g. Burke and Beard, 1979) and during the treatment of various conditions (e.g. Gabel and Kakoschke, 1996)”. There are a few attempts in such areas, like cosmetics improvement of dis-functional jaw structures (Coombes et al., 1990), identification of physical or psychology conditions within the population (Shaner et al., 2000), etc.

In our case, the area of interest (lower part of face) needs to be recorded in the common part of two or more images consecutively, since its shape is a time dependant function, and it changes dynamically while one performs oral activities such as speech or laugh etc.

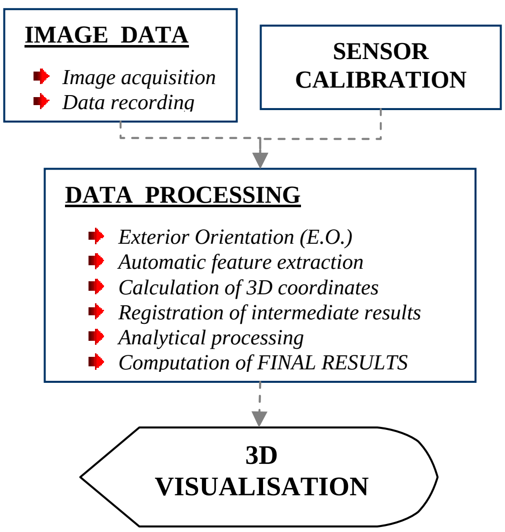

Fig. 1 Application Workflow

Parameters that have to be taken into consideration may be grouped in three basic categories:

1. **Geometric** issues such as, sensor resolution and specifications, camera placement and orientation of optical axes, technical specifications of the arrangement used for mounting of the sensors during data acquisition, accuracy specifications concerning the construction of the calibration field etc.
2. **Radiometric** issues i.e. radiometric properties of surfaces that lead either in non-homogeneity within areas of the same object, or resulting in the presence of high similarity between adjacent areas of different type, illumination conditions etc.
3. **Synchronization** issues due to the necessity for simultaneous image capture from all sensors

The complexity of the venture derives from the fact that all above related requirements have to be met at the same time while maximum automation in data processing has to be achieved as well. The workflow in general is shown in figure 1.

3. PROJECT PLANNING AND DATA ACQUISITION

Throughout the research process, we have put a lot of effort in order for the whole system, including devices being used, S/W applications and H/W parts, not to exceed the standards of implementation in terms of low cost while no compromises should be made in accuracy related issues.

Therefore, the choice of two (2) **SONY DCR-HC30E** commercial camcorders is completely justified. The sensors, equipped with i.LINK (DV) OUT can be connected with a PC and deliver images with a resolution of **720 x 576** pixels. Given the fact that the corresponding width of the area being recorded does not exceed the size of **8cm** (80.000 microns), we easily jump to the conclusion that pixel size at the object space is about **100 microns**.

A **highly accurate CNC** machine *(Computer Numerical Control)* has been used for the construction of the **calibration field.** The accuracy of the construction is of the order of some decades of microns. The **24 3D control points** being used are arranged in **4 lines** and **6 rows.** The **maximum planar distance** between them is **5cm** while **heights** vary from **0** to **2,5cm** giving thus a very satisfactory **width to height ratio** of the order of **50%.**

SONY DCR-HC30E also provides controls for manually focusing and setting the preferred exposure level, by disabling the **AF/AE** *(AutoFocus/ Automatic Exposure)* functions. This is very useful because the interior orientation of the sensors needs to be **fixed** and it is trivial for the synchronization of image capturing.

Sensor positions are **arranged** in **vertical** direction. Thus, **epipolar lines** appear in vertical directions as well. In our case, this is mandatory for the search for homologous points using the correlation coefficient image matching technique with epipolar constraints, since **lower lip contour** or **lower visible acme of upper lip** (***L.V.A.L.***)**,** that needs to be traced over all consecutive stereo-pairs, appears in the horizontal direction as shown in figure 2. Search is carried out among the epipolar line which intersects with the ***L.V.A.L.*** almost perpendicularly so that homologous points are well defined.

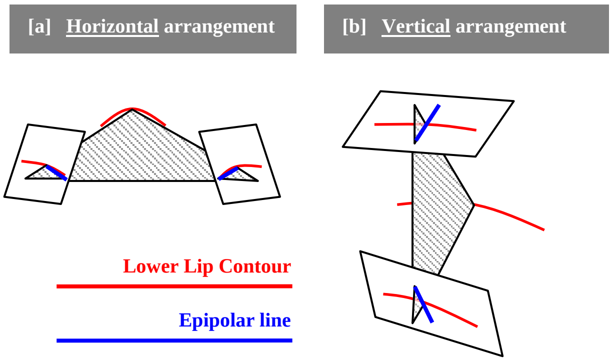

Fig. 2 Geometry of epipolar lines in regard to sensors positions

Segmentation of the area of upper lip and extraction of ***L.V.A.L.*** at the reference image of each stereo-pair needs to be handled in a fully automated way. The more precise various components of the area of interest are defined, the easiest and more successfully they can be separated from each other without the need for human interference. Concerning ***L.V.A.L.*** tracing process, we have experimentally concluded that the best results can be obtained if black colour is applied using a soft pencil crayon and eye shadow powder over it so that finally upper "black" lip surface is as less reflective as possible. That way, the separating line formed by points at the lower visible positions (***L.V.A.L.***) can easily be detected, even when upper lip is located over gingiva which would have otherwise been impossible (fig. 3).

Fig. 3 Colourization of upper lip

Finally, synchronized image capturing is carried out by taking advantage of the possibility to connect both cameras directly on the PC. Therefore suitable software has been developed for performing all necessary controls for synchronized digital image recording (fig. 4).

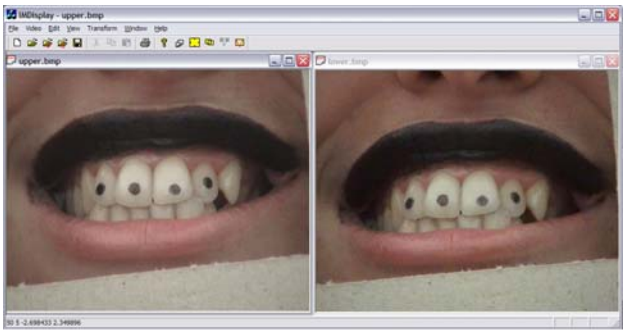

Fig. 4 Synchronized Image Capturing s/w application

4. METHODOLOGY - DATA PROCESSING

Exploitation of image data is being carried out in successive, mostly automated, steps through a highly sophisticated photogrammetric workflow.

4.1 Sensor Calibration and Exterior Orientation

By using a stereo-pair of shots over the calibration field it is possible to estimate the parameters of the exterior orientation of the sensors while at the same time calibration is carried out in one step, through a **bundle adjustment** with **simultaneous system self calibration** using an **additional parameter model.**

Implementation of a **best fitting ellipse algorithm** allows for the automatic measurement of signalized control points coordinates (fig. 5).

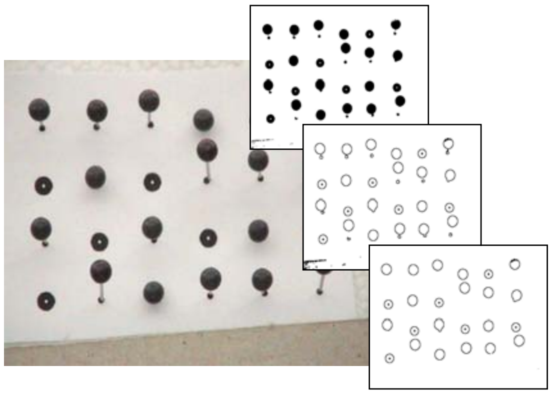

Fig. 5 Coordinates of experimental signalized control points measured using best fitting ellipse algorithm.

Accuracy of E.O. results has proved to be of the same magnitude as the accuracy of the 3D signalized control points coordinates at the experimental calibration field.

4.2 Landmarks

Realistic restitution is a very important issue. Results need to be presented along with existing physical points and/or shapes whose position does not vary. These are called **Landmarks**. Corners of teeth or the separating contour between teeth and gingiva can be used as such retaining therefore, that results can be understood directly by dentists.

Landmarks can be extracted automatically or manually as shown in figures 6 and 7, depending on the patient's mouth clinical condition (i.e. missing teeth etc.)

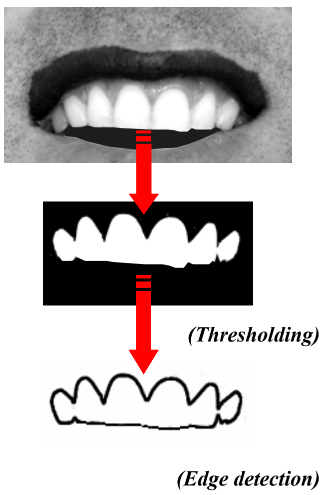

Fig. 6 **Automatic** Landmark Localization

After landmarks have been selected, regardless of the way chosen, and point positions are located at the reference image, homologous points are automatically identified on the other image using **correlation coefficient algorithm** with **epipolar constraints** and corresponding image-coordinates are measured. This only needs to be done once.

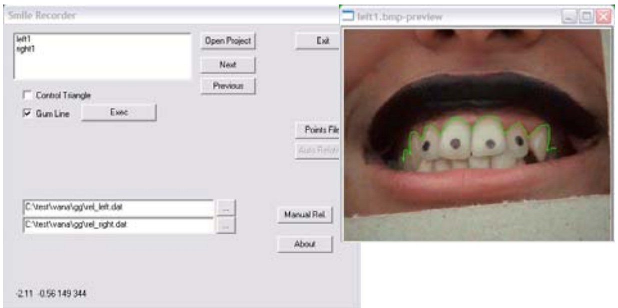

Fig. 7 **Manual** Landmark Localization

4.3 Reference Points

Bare shifts of head position between consecutive frames, are always present. This fact, results in computation of every 3D ***L.V.A.L.*** in slightly offset position compared with each other. Therefore, it is necessary to eliminate this source of additional errors. One can actually visualize that having in mind that 3D results from all successive frames have to be registered in respect with the exact position of the patient's head in the first frame. This is the same if we could somehow stabilize in 3D space the position of the upper part of the denture, allowing at the same time lips to move and deform freely during performance of speech, laugh etc.

In order to achieve this, there is the need to establish **reference points** which have to be unique, well defined and visible in all successive frames. This task is carried out manually by the operator and once again, the **correlation coefficient algorithm** with **epipolar constraints** is used to identify homologous points. Corresponding image-coordinates are measured and 3D coordinates are then computed since the elements of the E.O. have already been calculated. Measurements of 3D coordinates of these points are used to compute the **6 parameters** (3 shifts ***DX***, ***DY*** and ***DZ*** - 3 rotations ***Dω***, ***Dφ*** and ***Dκ***) of a **rigid body transformation** which is then applied on the results of each stereo-pair. Though reference points are measured in every stereo-pair, they only need to be located once. After that, they are being automatically identified in each successive frame through a point **tracking algorithm**.

Thus, variations of the positions of ***L.V.A.L.*** points due to head movement can be subtracted and the remaining variation will represent the true relative translation of ***L.V.A.L.*** in respect with gingiva and teeth.

4.4 Extraction of L.V.A.L in Successive Instantaneous Positions.

The algorithm that has been developed for ***L.V.A.L.*** extraction, utilizes the fact that significant variations of intensity values are present between different areas (i.e. lips coloured black, red gingiva, white teeth), and operates in the following manner:

Given the pixel previously selected as the first reference point, a starting point is created and a search begins in the vertical direction of the corresponding row containing the pixel. The search involves the intensity values in all or some selected colour channels (R-G-B). Because of the black colour used for the lips, corresponding pixels are expected to hold small intensity values, especially when compared to those of pixels that belong to adjacent areas like gingiva or teeth. Experimental results have shown that in most cases setting a threshold of about 70 over intensity values on the Red channel is sufficient enough ($R<70$). The first pixel to fall short that limit is considered to be ***L.V.A.L.*** point.

After that, the starting point is shifted by a given step (i.e 5pixels), and the search is repeated. At the end of each loop, the slope of the line joining each new point with the previous is calculated. When the slope exceeds a threshold value set by the operator (i.e. 30%) the algorithm assumes to have reached the end of the area of interest. It then returns to the starting point and the process is repeated while the only thing that changes is that the position is shifted towards the opposite direction. When the above criteria are met once again the ***L.V.A.L.*** has been extracted from the current frame (fig. 8).

Fig. 8 Automatic extraction of ***L.V.A.L.*** points (red)

Thereinafter, homologous points are located using an implementation of the **correlation coefficient algorithm** with **epipolar constraints.** An example is shown in following fig. 9. The task is executed for each stereo-pair. Conclusively, up to this point, the following have been calculated:

a) 3D coordinates of **Reference Points** for each frame
b) 3D coordinates of **Landmarks**
c) 3D coordinates of ***L.V.A.L.*** **points** for each frame

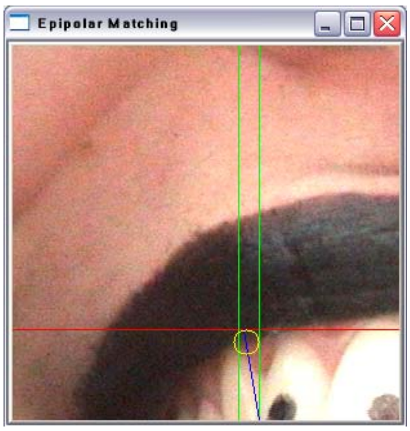

Fig. 9 Implementation of the Correlation Coefficient Algorithm with Epipolar Constraints used for Image Matching

4.5 Gingiva Maximum Exposure Contour *(G.M.E.C.)*

Let L_i the list of the coordinates of the ***L.V.A.L.*** as they calculated with the above described procedure and R_i the list of the coordinates of the reference points for the frame ***i***, while R_0 is the list of the coordinates for the reference points on initial frame. **Rigid Body Transformation** is applied to every L_i using it's R_i in order to transfer all the coordinates under a common coordinate system (which is defined by the R_0), giving a new L'_i. Every L'_i then is sorted using the ***x*** coordinate of the points.

The **Gingiva Maximum Exposure Contour** (***G.M.E.C.***) is calculated then as follows: Let ***C*** the list of the points that describe the ***G.M.E.C.*** where C_n is the ***n*** point in the list and ***d*** is the maximum distance (in x axis) between the points that will describe the contour. The most left (C_0) and most right (C_N) point of the contour will have the minimum and maximum ***x*** coordinate respectively, calculated from the L'_i.

$$x_{\min} = \min\left(x_{\min i}\right) \quad ; \quad x_{\max} = \max\left(x_{\max i}\right) \tag{1}$$

The ***G.M.E.C.*** will consist of ***N*** points, with

$$N = \left(x_{\max} - x_{\min}\right)/d \tag{2}$$

Next step is thickening all the L'_i. New L''_i are calculated and each one of them consists of ***N*** points. These points are calculated by interpolating each L'_i using Langrange polynomial or simple 3-d line interpolation for faster operation.

Then, the C_n point coordinates are calculated as follows:

$$\begin{aligned} x &= x_{\min} + n * d \\ y &= \max\left(L''_i[n].y\right) \\ z &= L''_\alpha[n].z \end{aligned} \tag{3}$$

with ***a*** equals the number of the frame that found in ***y*** calculation or

$$z = \max\left(L''_i[n].z\right) \tag{4}$$

in case that the maximum exposure in z axis is wanted, too.

The $L''_i\,[n]$ function returns the point in position n of the L''_i.

4.6 Results

Once the analytical process is complete, results can be visualised in various ways. An example is show in fig. 10 where different 3D views are generated combining 3D coordinates from points modelling the limit between gingiva and teeth *(green)* along with coordinates of calculated **Maximum Exposure Contour** *(magenta).*

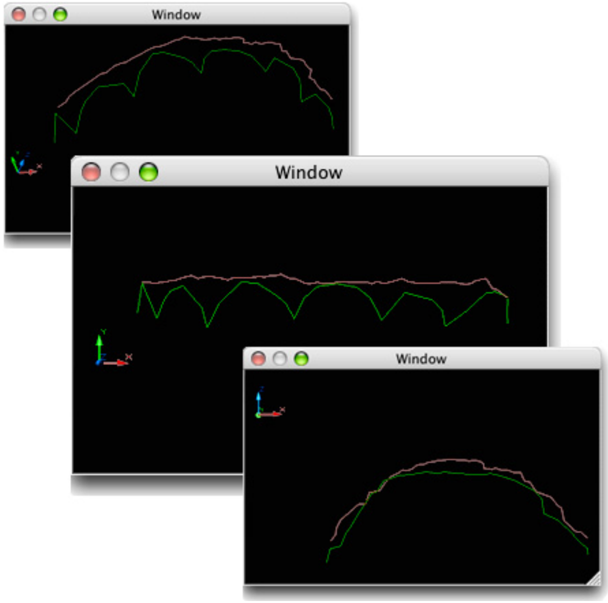

Fig. 10 Results: *Isometric* (top) /*Front* (middle) /*Plan* (bottom)

The first element group plays the role of the ***Landmark***, i.e. if one needs to know up to what extend a person's gingiva is being exposed, all he has to do is measure as many vertical distances as he likes, beginning from points on the green line. All measurements are on 1:1 scale so results can be transferred "as is" in the real object, the person's mouth. By that way, results can be easily and directly interpretable in a physical way by dental experts and medical stuff.

5. EVALUATION IN TERMS OF DENTAL SIGNIFICANCE

The subjects of all relative to smile studies attained a smiling position after usually being asked to laugh with lips in maximum tension. In this way, no specific 'lip borders' were defined, complicating the precise and accurate reproduction of this particular lip position, which is considered significant in decision making for prosthetic restorations and implant placement. In addition, only border positions of the lips could be recorded, without any reproducibility and ability to capture all intermediate functional positions.

This limitation has induced unpredictable variations in lip size and lines as well as tooth or gingival display measurements. However, if the subjects were simply asked to laugh, the resulting smiles would have lead to either exaggerated or limited tooth/gingival display, depending on individual interpretation of the meaning of smiling (Kapagiannidis et al., 2005). On the contrary, an involuntary enjoyment smile, elicited from laughter or great pleasure, would probably cause greater expansion of the lips with maximum tooth and gingival display (Acherman and Ackerman, 2002). Thus, the dynamic recording of smile is necessary to capture all information useful in therapeutic applications.

The use of the developed system in relative research and diagnostic as well as therapeutic approaches provide a detailed recording of these parameters, expanded bilaterally to the most distal structures. Furthermore, teeth wear and gingival recession as pathological entities (Donachie and Walls, 1995, Kim et al., 2000, Pigno et al., 2001, Albandar and Kingman, 1988), in addition to aesthetics, could be recorded, evaluated and monitored at different time intervals. All the above and in combination to other anatomic features of soft tissues involved in smiling, such as amount of commissures upright lifting during smiling, could provide accurate, complete and additional information on aesthetic aspects that should be considered in dental fixed and implant prosthodontics.

6. CONCLUSIONS AND PROPOSED FUTURE WORK

The developed system provides for a full and accurate 3D recoding of all the medical parameters to be considered in research, diagnostic and therapeutic approaches. Once accuracy and reliability related issues are examined and dealt with in detail, further exploration of the developed system will be based on technological advances in digital imaging for real-time exposures, higher resolutions and a more user-friendly interface.

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