Photogrammetric 3D Digitization of Human Faces Based on Landmarks

L. M Galantucci, G. Percoco, E. Di Gioia

Abstract— **Anthropometry is an objective tool serving to evaluate the shape of the face and reveal changes observed in the subject over time, or among different subjects, analyzing quantitative and qualitative differences. It also permits the study of normal and abnormal growth, diagnosis of genetic or acquired malformations, planning and evaluation of surgical and/or orthodontic therapy, and verification of the treatment results by analyzing, measuring and comparing the face shape. Among 3D digitization technologies, photogrammetry shows great promise because it is a low cost, biocompatible, safe and non-invasive methodology, but it still suffers from a need for considerable human intervention. In previous research, the Authors illustrated a new approach based on a 3-Cameras photogrammetric system. After several tests, conducted to verify the validity of this methodology, the present experimental study was carried out using a re-engineered photogrammetric scanning system to obtain landmark-models of human faces, and comparing these results with those achieved with laser scanning, applied to a dummy face (in order to eliminate errors caused by breathing movements in a living subject).**

Two different, specifically designed experimental 3D photogrammetric setups have been developed and tested to enhance the performance. This research demonstrates the potential of low-cost photogrammetry for medical digitization; further research will be addressed to testing the use of the scanning system on humans to validate its clinical performance.

Index Terms—**3D Scanning, Biometry, Face Digitization, Landmarks, Orthodontics.**

Introduction

In recent decades, the availability of new digitization and measure systems has prompted the development of anthropometric research using 3D surfaces, aiming to study the 3D geometry and morphology of the main human external tissues.

Anthropometry reveals the face shape and the changes due to time, and allows genetic or acquired malformations to be diagnosed, as well as the planning and evaluation of surgical or orthodontic treatment, the study of normal and abnormal growth and verification of treatments results.

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Although the market in this special field is not yet sufficiently exploited [1], many research papers have already been published in literature, describing several approaches for anthropometric measurements that can be subdivided into two-dimensional, three-dimensional and hybrid approaches [2][3].

Reverse Engineering (RE), a technique that allows reconstruction of the CAD (Computer Aided Design) mathematical model of any existing object, enables the practical implementation of 3D anthropometry. In particular, 3D information can be retrieved about the facial characteristics of a person, allowing construction of a three-dimensional computer model of the human face. Medical applications require a similar 3D precision and accuracy to physical engineering: in this multidisciplinary approach the engineer designs and models physical products, and the doctor diagnoses and treats patients [4][5] using the physical, engineered products.

II. Background

Two-dimensional anthropometric approaches first emerged more than thirty years ago: essentially they use, as data sources, one or more images of the subject to be identified or measured; data are collected and compared with images of known people for the purposes of identification or recognition. The fast development of data processing technologies, techniques and methods has strongly boosted the implementation of 3D facial recognition. A great many methods have been proposed; the more promising and commonly used in literature are summarized herein.

As regards face matching, in crest lines analysis [6], a set of curves approximates the shape of a 3D object. This increases the real time performance of object recognition algorithms, since one can deal with a specific set of curves as opposed to the entire object. Crest lines are the loci of points on a surface whose largest principal curvature (expressed as an absolute value) is locally maximal in the associated principal direction. In the face recognition context, crest lines correspond to the boundaries between facial features. Since matching of surface shapes can be a complex task, one possible method is to apply fast curve matching algorithms to match crest lines on two surfaces. In fact, curvature profile analysis provides an efficient tool for a rapid comparison of shapes. The information about curvatures could also be exploited by another common methodology, i.e. feature extraction. For this, 3D data are segmented into connected subsets of meshes, called regions or features.

Another existing 3D technique is known as Volume Deformation Energy Cost. This methodology is based on finding out the “energy cost” required to deform one facial

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surface into another. This is a general method and can either be applied to complete face-to-face deformation or used to compare corresponding features. The energy required to pull or stretch two similar surfaces, one into another, would be low [7].

As regards the acquisition method, studies have been carried out by the Authors, evaluating two different scanning systems, namely photogrammetry and laser scanning, employed for the acquisition and the recognition of human faces [8] [9].

To gain information from 2-dimensional images a regular grid of points is projected over the face, and the correspondence between these points is identified, recognizing the same point on different photographs and determining its spatial localization.

For each person whose 3D information is available, two point clouds are plotted, coinciding with each side of the face, and each viewpoint of the grid projection. The two point clouds are subsequently merged (the stitching process described by Lane [4]) to obtain a single point cloud for each face. The equipment used for the photogrammetric acquisition is simple and low cost; one or more digital cameras, a projector device and photogrammetric software are enough to obtain the 3D information. The second methodology, used in that study only for comparison purposes, is the laser scanning technique, able to acquire 3D information about the shape of human faces. The authors used a manual Kreon sensor (model KLS51) and an automatic scanning system (Konica Minolta Vivid 910 i); both are based on triangulation. When using a laser scanning system, in order to achieve good acquisition, the person has to collaborate by staying motionless throughout the scanning (15 sec). In fact every small movement could produce errors in the resultant point cloud. A special device (cephalostat) is used to hold the head still during 3D acquisition. Results obtained using the two methodologies are analyzed and evaluated to determine whether, although it is a low-cost methodology, a photogrammetric technique is able to provide valid information about facial shape. Data processing is slower with the photogrammetric technique, but the information acquisition, that is the time spent to take the photographs, is very fast (1/5000 sec flashing time). This is an essential aspect, because the "object" acquired is a human being; in fact every movement of the head could make the work useless. Moreover, although less information about facial shape is obtained using photogrammetry, the points whose 3D information are acquired are equally spaced and cover the entire face and after estimation of their spatial localization, need no further processing. A process based on photogrammetry consists of five steps: (a) acquisition of facial images from different directions; (b) determination of the camera positions and calibration parameters; (c) detection of a dense set of corresponding points in the images; (d) computation of 3D coordinates; (e) generation of a surface model. As in an acquisition performed with a 3D scanner, the result of a photogrammetric acquisition is a point cloud, which is then meshed to construct the surface model. Although 3D acquisition and recognition systems have undergone major developments in the past few years, further improvements can still be achieved, such as cost reduction (currently very high), and decreased error in the recognition or authentication process.

Recently, the Authors have proposed a completely automated version of the 3D photogrammetric scanning System, also based on the projection of hybrid and regularly spaced grids [10] [11], to reproduce the whole human face for diagnostic purposes in orthodontics. Using this method it is possible to acquire information about the characteristics of the subject's soft tissues and to make exact measurements.

Nowadays, new methodologies that allow the facial characteristics of orthodontic/surgery patients to be recorded are gaining importance, as a means of comparing affected subjects with controls without using invasive technologies such as radiation.

In the present paper two 3D photogrammetric systems, developed by the authors for measuring soft tissue facial landmarks, are tested and compared with other commercial and research approaches,.

The landmarks high relief points can be obtained in three main ways: (i) extraction from a 3D facial model (according to Kovacks [12], Baik [5], Winder [13]); (ii) manual digitization onto the face (according to Sforza [14], [15]); (iii) placement of targets on the face [4].

To obtain surface landmarks (i) starting from a 3D full face surface model, it is necessary to follow a specific measurement protocol.

On the 3D facial models, the protocol illustrated in [5] is used. A consistent Coordinate System is obtained starting from the Nasion N' as zero point, and establishing the axial referenced-plane by rotating Camper's plane (right nasal ala - both tragus points) 7.5° upward on the axis formed by both tragus points. The sagittal referenced-plane passes through the soft tissue N' and the midpoint of both tragus points; it is also perpendicular to the axial referenced-plane. Finally, the coronal referenced-plane passes through N' and is perpendicular to both the axial and sagittal planes (Fig. 1).

Most landmarks used in this study were proposed by Farkas [16]. Simply connecting the landmarks and then calibrating the size (height, width, depth), it is possible to create a simplified 3D facial landmark model; subsequently it is necessary to carry out superimposition, to compare the landmark model to the patient's full face model [5], so as to verify the reliability of the information thus obtained.

The aim is to facilitate a clinical diagnosis for orthodontic/surgery purposes based not only on absolute values (linear-angular distances related to a standard range of measurements), but also on relative values (angles and

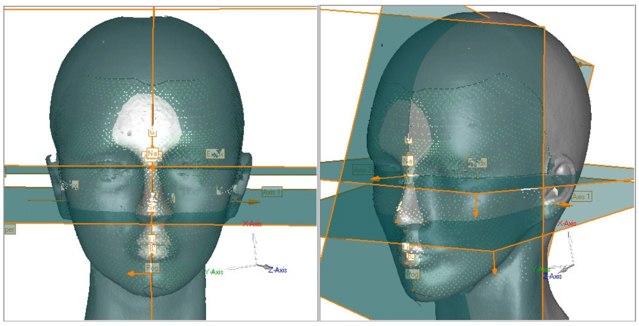

Fig. 1: Landmarks, referenced planes & coordinate system on the 3D model of the acquired mannequin head using the method reported in [5].

proportions, to make a 3D soft tissues template that can be related to an average normo-face, that is different for each population) [17].

As regards manual digitization onto the face (ii), in a previous study on soft tissue facial shape based on manual digitations, Ferrario et al. [18] reported that 3D measurements values were not sensitive to head position. Nevertheless, Natural Head Position (NHP) is better exploitable: in fact, if the subject changes his position, the soft-tissue attached to the bone will be stretched or constricted, and soft-tissue drape could also be changed [5]. Moreover, NHP is the most reproducible head position and it is the face's natural orientation for treatment planning [4].

In the recent Ferrario-Sforza Method, described in [15], a 3D computerized electromagnetic contact digitizer (3 Draw Polhemus) is used to collect 50 soft tissue landmarks previously individuated by an expert operator by direct inspection or palpation of the patient's facial soft tissue.

Both for the first [18] and second [15] method the operator needs to be very experienced, and able to identify natural facial landmarks with the greatest precision and accuracy.

Using method (i) it could be difficult to recognise them on the 3D virtual facial model instead of directly on patients, while if method (ii) is adopted the major difficulty lies in the variability of the pressure applied by different operators during direct anatomical landmark digitisation, that can modify the registration of the anatomical landmark position due to the elasticity of facial soft tissues.

For these reasons, in this study the Authors have decided to adopt method (iii).

III. PROPOSED APPROACH

In this study a particular 3D photogrammetric scanning system is presented, that can offer a low-cost solution for craniofacial studies, basing measurements only on few landmarks previously identified and marked on the face using coded targets, and measured without contact.

The landmarks have been described in [18], where a direct manual digitizing technique based on an electromagnetic touch probe instrument is used. In that case the time required for the measurements is very high (some minutes even with an expert operator and collaborating patients). On the other hand, the 3D photogrammetric method does not need an expert operator and collaboration of the patient is not important, because the speed of the takes is such that movements do not pose a problem.

In Fig. 2 thirty coded targets, used to underline the position of the landmarks, are shown; they were chosen to detect the facial characteristics, namely:

- front, **tr** trichion, **g** glabella, **ft** frontotemporal
- eyes, **ex** hexacanth, **en** endocanth, **os** upper orbital
- nose, **n** nasion, **prn** pronasal, **sn** subnasal, **ac** head of nasal wing, **chp** head of nasal filter
- lips, **ls** upper lip, **li** lower lip, **ch** cheilion
- chin, **sl** sublabial, **pg** pogonion, **me** menton
- lateral surface, **t** tragion, **chk** cheeks, **go** gonion

Two different 3D photogrammetric setups have been experimented by the Authors. Both have been exploited to scan faces with dense point clouds and compare them with the landmarks.

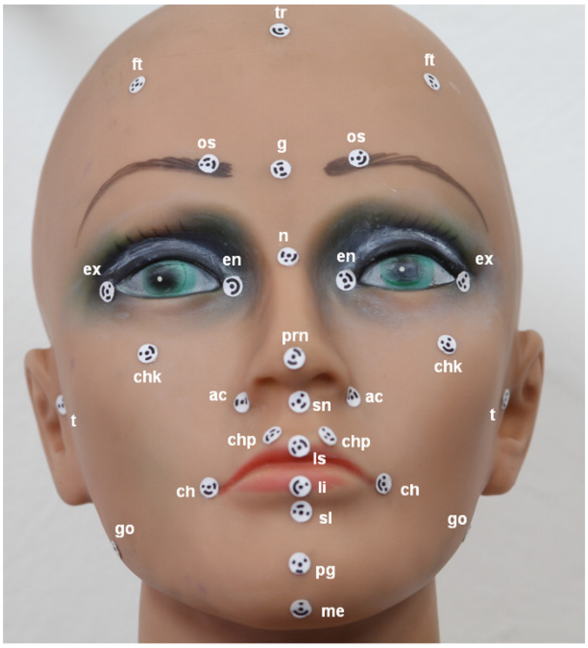

Fig. 2: Facial landmarks

A. First Experimental setup

In the first setup a specially designed digital 3D photogrammetric system was used, in order to evaluate the performance of this technique when applied to the 3D computer modeling of human faces and face recognition. Three digital cameras were used to capture the images: two “Nikon Coolpix 4500” and a “Nikon Coolpix 990”. 3D data were reconstructed utilizing the commercial software Photomodeler.

Normally, the first step of a photogrammetric process is images acquisition from different directions. In this case, the reconstruction of a 3D model of each human face was made starting from the acquisition of three photographs, each one taken from a different direction.

The 3D image acquisition of human faces is more critical as compared to image acquisition of a static object: in fact it is necessary to “freeze motion”, that is to avoid breathing and moving effects [4], [17]. If the images are captured at different instants, there could be errors due to major movements (changing the head position) or minor movements (muscle activity, skin or hair surface variation) [12], [15]. Furthermore, any movements could cause errors, due to shifting of the grid projected on to the face. Therefore, a good 3D reconstruction can actually be performed only if the acquisition of photographs is done simultaneously [19].

The three digital cameras were fixed on a single support, designed to accommodate the necessary angulations of the cameras and placed at a suitable distance from the person to be photographed. To cover a wide area of the face [20], the cameras were positioned on a circumference arc with the subject’s face in the centre. The central camera was positioned in front of the subject; the lateral ones at an angle of 30° [9], [10], [11].

The only hypothesis required during the acquisition sessions was the Natural Head Position and expression of the subjects, which is the most frequent situation represented when the system is employed for personal identification.

For each person three image acquisition sessions were performed [8].

The photographs related to the same person were taken on the same day. Therefore, although time is a factor that affects the results
[17], in this case it did not need to be taken into account. The 3D localization of grid points projected over the face was determined using an automatic referencing procedure. Manual referencing helps to improve the referencing process, when automatic referencing is not able to establish the 3D localization of every possible point of the grid projected over the face. After the referencing stage, when 3D points are created, input data are adjusted and errors are minimized.

After a previous calibration and orientation of the cameras, the photogrammetric software Photomodeler 5.0 processes data related to the reference points and calculates their spatial localization.

For each person analyzed, two models related to full face (one for each acquisition session) were created on the basis of the 4316 points grid [8] (Example in Fig. 3).

However, the reconstruction process is not completely automatic. During the orientation stage, the software requires correspondences among a few initial points to be specified, so as to establish the 3D orientation of the cameras. These correspondences must necessarily be obtained with a manual procedure. When the 3D position of the cameras is known, an automatic referencing procedure can be set up for most of the projected points.

B. Second Experimental setup

Due to the above-mentioned drawbacks and in order to make the system more robust and industrially valid, the scanning system was re-engineered and firstly applied only to a dummy head (Fig. 4). The new 3D photogrammetric system consisted of three 10 megapixel CMOS sensors of commercial cameras and one coded flash projector synchronized with the cameras by the software. To increase the target visibility on the investigated surface, the image acquisition was done only by the light of the projector.

Preliminary automatic orientation of the images is performed exploiting a specifically designed, retro-illuminated pattern. The entire point cloud was compared to the landmarks to establish the mean error. The images were acquired with the same procedure used in the preceding cases, but in this case the environment was completely dark, to enhance the contrast.

Instead, the landmarks were acquired using room light conditions, and taking three photographs. Digitization yielded a point cloud consisting of 2430 points (Fig 5).

Moreover, the dummy head was digitized both with a photogrammetric technique and with the laser scanner Minolta Vivid 910i. The textured laser scanned point cloud is shown in Fig. 6.

One of the main problems with projected targets photogrammetry is the low contrast of the targets on the human face surface.

For this reason the second experimental procedure was done by directly placing targets on the face, as shown in Fig.2, and then acquiring the facial images using photogrammetry (Fig. 7, 8).

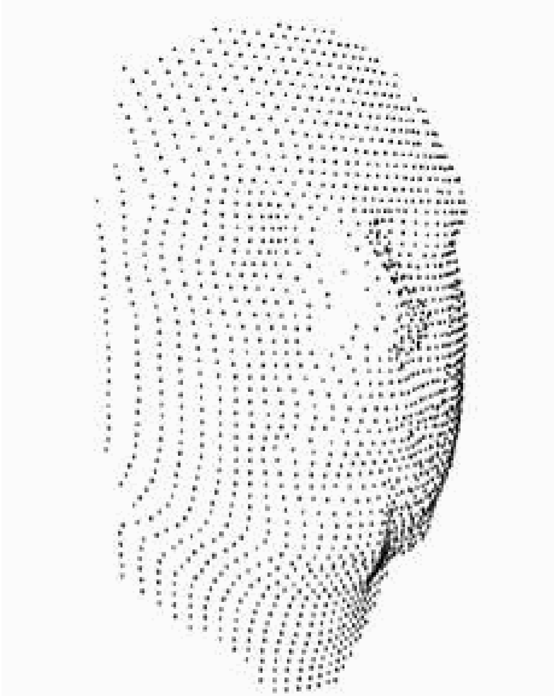

Fig. 3: Example of a dense point cloud

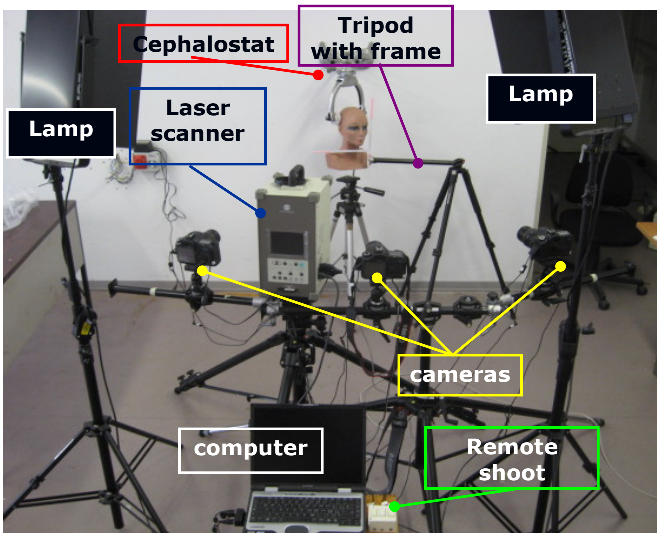

Fig. 4: The re-engineered scanning system

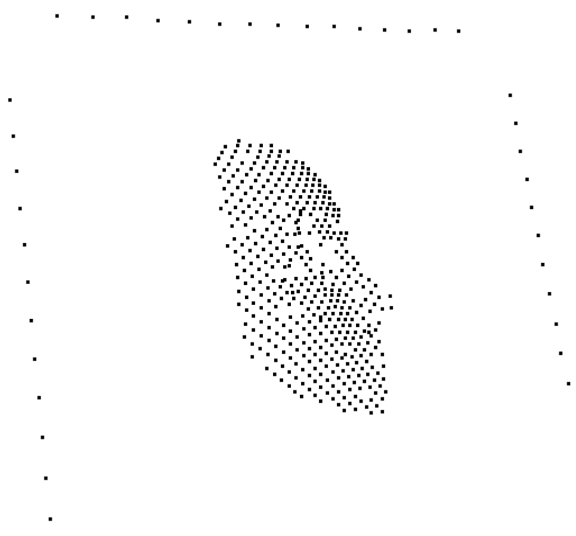

Fig. 5 Photogrammetric point cloud with the second setup

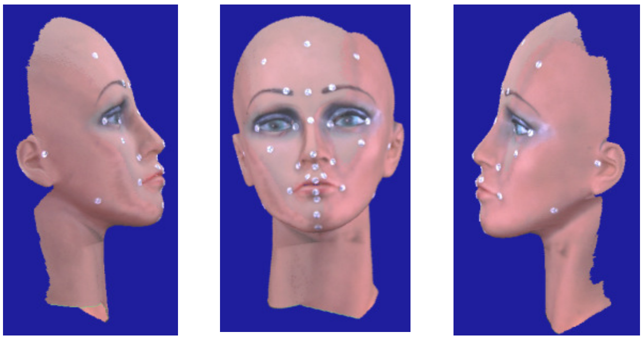

Fig. 6: Textured laser scanned point cloud

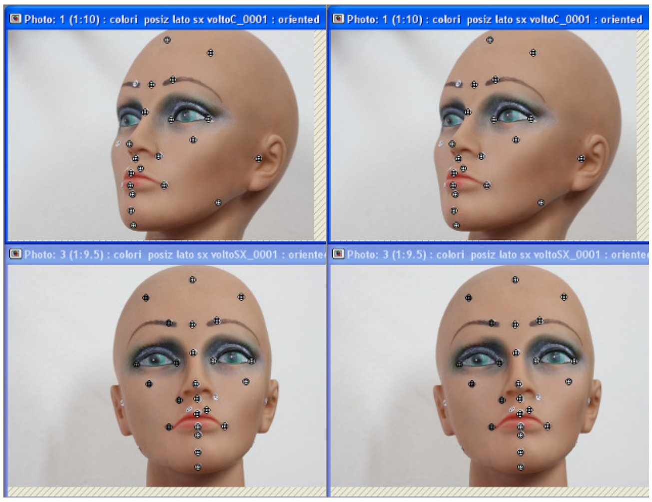

Fig. 7: Landmark photogrammetric acquisition for the left side of the face

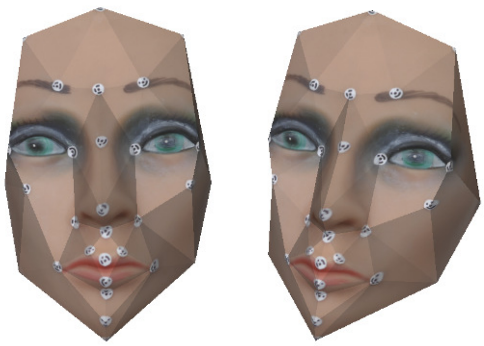

Fig. 8: Textured photogrammetric 3D landmarks face model

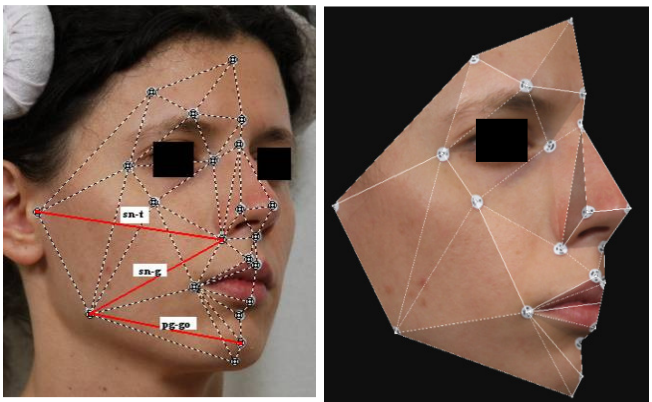

Fig. 9: Angle measurement done on a real face

Table I: Results with the reengineered scanning system

Landmarks distances [mm]	Obtained by Photogrammetry	By Laser	Difference
ac[Rt]-ac[Lt]	29.61	30.3	0.7
ex[Rt]-ex[Lt]	97.15	98.1	1.0
en[Rt]-en[Lt]	30.60	31.0	0.4
ex[Rt]-en[Rt]	35.06	35.8	0.7
ex[Lt]-en[Lt]	33.70	33.7	0.0
tr-g	44.91	45.2	0.2
g-n	25.33	25.7	0.3
n-prn	34.84	34.1	0.7
prn-sn	13.01	13.3	0.3
li-sl	7.18	7.4	0.2
sl-pg	13.28	13.8	0.5
pg-me	11.97	12.2	0.2
n-me	93.24	94.3	1.1
tr-n	70.07	71.1	1.0
n-sn	41.33	41.5	0.1
sn-me	43.43	42.0	1.4
t[Rt]-go[Rt]	62.08	62.7	0.6
t[Lt]-go[Lt]	55.50	56.4	0.9
go[Rt]-me	70.23	70.4	0.1
go[Lt]-me	74.32	75.2	0.8
t[Rt]-t[Lt]	126.51	128.0	1.4
chp[Rt]-chp[Lt]	14.77	15.6	0.8
ch[Rt]-ch[Lt]	46.36	47.1	0.8
os[Rt]-os[Lt]	40.75	41.2	0.4

The subsequent phase consisted of measuring segments connecting the several points, like those used in the medical field to point out the individual anatomical characteristics and/or malformations.

In this case the measurements were performed to obtain, from the landmarks spatial coordinates, the values of the distances and angles measured using photogrammetry versus laser scanning on the same dummy head. The distance values are reported in Table I.

The maximum linear difference between measured distances was equal to 1.4 millimeters, while the mean was equal to 0.6 millimeters. With the previous technique the mean between the differences was equal to 2.5 millimeters: so the presented 3D photogrammetric system resulted very much better.

The comparison among the measurements of some distances done manually with a caliper, or with the photogrammetry and laser scanning measurements, is shown in Table II.

Fig. 9 and Table III illustrate an example of angle measurements done on a real subject's face.

When considering the accuracy of the two methods, it should be noted that Konica Minolta declares accuracy measurements for the Vivid 910i laser scanner in the ranges X: ± 0.38mm Y: ± 0.31mm Z: ± 0.20mm, while with the scheme adopted herein it is possible to calculate an accuracy for the photogrammetric system equal to almost 1/10000, that means, for the face, ±0.15mm on Z and ±0.03mm on X and Y with a confidence level of 95%, assuring highly accurate facial measurements.

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Table II: Results with some landmarks manually measured

Land marks distances [mm]	Obtained by Photo-grammetry	By laser scanning [mm]	Manual measure with caliper	Max difference
n-sn	41,33	41,5	41,51	0,2
t[Rt]-go[t]	62,08	62,7	61,75	0,9
chp[Rt]-chpLt]	14,77	15,6	15,23	0,5
os[Rt]-os[L]	40,75	41,2	40,87	0,3

Table III - Three dimensional angles

Measured Angles [mm]	Using Rhino CAD	Using VIVID 910 Laser scanner
g-n-prn	161,31°	160,5°
n-prn-pg	139,55°	138,5°
go[Rt]-pg-go[Lt]	83,06°	84,7°

IV. CONCLUSIONS

In this paper the validity of photogrammetry for digitization of human faces is demonstrated.

The 3D analysis of facial soft tissue morphology is a precious instrument for clinical purposes, since it is a non-invasive method. Landmark analysis of the human face is a widely used methodology in the medical field in such areas as orthodontics and surgery, being a valid method for making a correct diagnosis and supporting treatment planning, as well as analyzing facial symmetry or asymmetries, and the presence of cranio-facial malformations.

Three-dimensional information regarding each subject can be retrieved, so making subject recognition possible based on the unique features of each face.

Digitization has been performed using 30 landmarks as indicated in literature, and comparing two technologies, namely low-cost photogrammetry and laser scanning, used on the same dummy head.

One of the main drawbacks of photogrammetry is the poor contrast of the targets on the human face surface. Two specifically designed different experimental setups are presented, demonstrating the better performance of the second one applied to a dummy head. This research points out the potential of low-cost photogrammetry for medical digitization. Further research will be addressed to testing the use of the second scanning system on humans to validate its performance.

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