Available online at www.sciencedirect.com
SciVerse ScienceDirect
ELSEVIER
M. Pesce et al./Procedia CIRP 00 (2014) 000–000
www.elsevier.com/locate/procedia

3rd CIRP Global Web Conference

A low-cost multi camera 3D scanning system for quality measurement of non-static subjects

M. Pesce[a,]*, L. M. Galantucci[a], G. Percoco[a], F. Lavecchia[a]

[a]*Politecnico di Bari, Dipartimento di Meccanica, Matematica e Management, Viale Japigia 182, Bari 70126, Italy*
* Corresponding author. Tel.: +39-080-596-2764. *E-mail address: marta.pesce@poliba.it*.

Abstract

In medical field, a growing interest is now focused on non-invasive diagnostic 3D image-based methods. The aim of this work is to develop a powerful, easy and low cost scan-system, based on close-range photogrammetry, capable to perform a complete acquisition of a non-static subject over 360°. The proposed scanning system has some advantages compared to the scanning systems traditionally used in medical field for human application, it is a non-invasive systems alternative respect to laser and structured light scanners, and demonstrate to be accurate and reliable for medical diagnostic application on human body.

© 2014 The Authors. Published by Elsevier B.V.
Selection and peer-review under responsibility of the International Scientific Committee of the 3rd CIRP Global Web Conference in the person of the Conference Chair Dr. Alessandra Caggiano.

Keywords: Close range stereo-photogrammetry; Low cost body scanner; Camera calibration; High accuracy measurement; Human applications; In vivo scanning.

1. Introduction

Digital human modelling is very useful in the areas of customized textile product design, multimedia games, and virtual reality [1], as well as in medical (orthodontics, orthopedics, surgery, etc.), human engineering, anthropometry and forensic applications [2],[3].

A study over three different scanning systems, laser surface scanning (Minolta Vivid 900), Cone Beam Computed Tomography and 3D stereo-photogrammetry (Di3D system), shows that non-contact methods are so accurate and reliable that they can be used for research and clinical use as well [4]. The human body is a living organism in constant motion; it is subject to variations in shape from external (gravity) and internal factors. Shape variations of a subject are induced by changes in facial expression, sway, respiration, body fluid distribution, shifts in pose, pulsation of the blood and motor reflex correction for control of postural stability. So, subjects' involuntary movements can potentially influence measurements and this is the most invalidating source of error in a scan of a non-static subject [5]. It would be possible to minimize this problem by using a glass support which fix the subject during the scanning process, without blocking the scanning light [6], but this solution presents other problems related to refraction errors introduced by the glass. The best solution to this problem seems to be provided by photogrammetry.

In [7]-[9], the authors presented a 3D photogrammetric face scanner, and demonstrate that among non-contact method, stereo photogrammetry is a very suitable technique for human scanning, because of the possibility to reduce the errors related to subjects' involuntary movements, as well as the possibility to avoid the risks related to the patient exposition to ionizing radiation, arising from the use of non-contact method such as X-ray tomography, traditionally employed for human scanning in medicine.

There are different photogrammetric scanners which can be used in human applications: Cyberware, Vitronic, Hamano and TecMath which use a laser projection systems or TC2, Wicks and Wilson, Telmat, and Hamamatsu which use a light source and various techniques for capture. Anyway, these scanners differ

2212-8271 © 2014 The Authors. Published by Elsevier B.V.
Selection and peer-review under responsibility of the International Scientific Committee of the 3rd CIRP Global Web Conference in the person of the Conference Chair Dr. Alessandra Caggiano.

considerably in price (US$ 50’000 – 410’000), resolution (1 - 8 mm) and speed (0.2–3.0 s) [10].

In a previous work, a whole 360° body scanner, stereo photogrammetry based, was presented by Percoco [11]: six uEye UI-1480 video-cameras were used to obtain a whole 360° three-dimensional model of an human body. In that work it was shown how stereo photogrammetry technique can be applied over a human body, to meet the growing needs of mass customization in apparel industry.

In this paper a powerful, easy and low cost scan-system, based on close-range photogrammetry, has been developed, with the purpose to perform high accurate measures over non-static subjects, suitable for digital human modelling in medical field, such as post-operative evaluation of surgeries (e.g., breast augmentation, abdominoplasty, etc.), or to make custom medical devices (e.g., corsets for the scoliosis correction or other posture problems). The study was organized into two steps: first, it was realized a particular calibration process which allowed to achieve high accuracy camera calibrations, and then, it was studied the precision and the accuracy of the proposed body scanning system, for application over both, static and non-static object.

2. Equipment

The quality of the digital camera greatly influences the result that it is possible to achieve with a photogrammetric scanning system: high quality cameras and high quality lenses, assure better image quality (less distortion and aberration) and thus, allow to obtain a very accurate 3D digital model. But the higher the quality of the equipment, the higher would be the cost of the same.

The proposed body scanning system has been made trying to reach a compromise between the accuracy and the cost of equipment. For this purpose, eight low cost digital cameras (Canon Power Shot A480) have been used. Canon Power Shot A480 has 3648x2736 Pixel resolution, and result suitable for a photogrammetric multi-camera system, for their handling and size (Dimensions = 92 x 62 x 31 mm, Weight = 140 g). The lens is an ultra-wide angle (focal length of 6.6mm), suitable for very large scenes. The aperture is f/3, that means a large aperture that allows to let in more light with a sufficient depth of field. The sensor of a camera greatly influences the quality of the photo. Bigger sensors generally produce better photo quality, but the bigger the sensor the higher the price. Moreover, larger sensors require larger cameras (because requires a larger lens and more space for supporting electronics), and this reduces the handling and the suitability for a multi-camera system. Once again, the choice of a Canon Power Shot A480, with a Charge-Coupled Device (CCD) 1/2.3" sensor format (1.69 10^{-3} mm Pixel size), represents a compromise having an acceptable accuracy and the lowest cost of equipment.

The cameras were mounted in pairs on a tripod, with a B distance between the cameras, and the H distance of the object having B/H approximately 0.2 (Fig. 1), and with a low separation angle. The four tripod were then positioned at ±45° and ±135° respect to the subject, with the aim to obtain a good overlap of the images, a very important condition for the success of the project [12].

Moreover, four white light lamps were used in addition to the flash supplied with the cameras, to ensure optimal and homogeneous exposure conditions. Finally, to synchronize the shots of the cameras, a modified firmware was installed on each device. This allowed the remote release by cable, on USB gateway, driven by a remote control. The data transmission to the computer, was carried out through the wireless SD cards installed on the cameras.

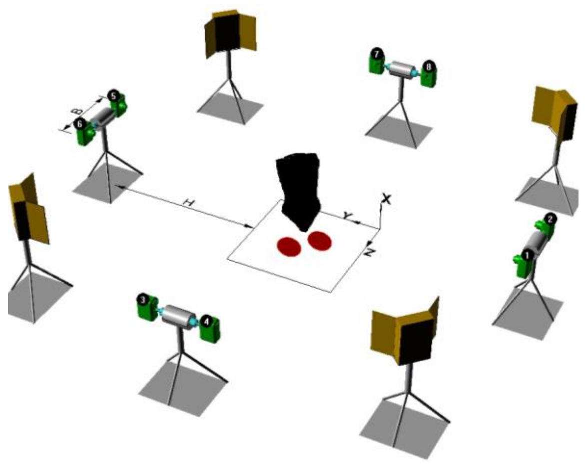

Fig. 1. Layout of the body scanning system.

3. The cameras and optics calibration

The camera calibration is a very important factor, which affect the accuracy of a photogrammetric scanning system, especially when low cost consumer cameras are used. This process is useful for building a physical model of a pair camera/lens, through his geometrical parameters, which is essential in order to correct some systematic errors, generated by lens distortions and aberrations. Thus, the more accurate is the camera calibration, the more precise and accurate will be the final result.

The cameras of the proposed body scanner system were calibrated with a two-step calibration process (as suggested by PhotoModeler Scanner® 2010). The first step is the Self-Calibration (SC), done with flat sheets with dots, followed by a second one, called Full-Field Calibration (FFC) performed with a 3D calibrator.

The FFC allows to calibrate the cameras with 3D specimen, having similar dimensions of the real objects to be scanned, at the distance and focus setting that will be used for the real future applications. Both calibration processes, SC and FFC, are articulated into two phases: in the first one (manual phase) the operator take the pictures, in the second one (automated phase) the pictures are acquired and processed by the software.

The manual phase was conducted by fixing each camera, one by one, on a tripod, while the calibrator was fixed to an articulated joint. Then, a set of photos was acquired with each camera, by setting the focus center coincident with the center of the subject.

The automated phase was carried out with the photogrammetric software PhotoModeler Scanner® 2010, which calibrates the cameras and optics on the basis of the D. C. Brown model [13]. This model take into account the following internal orientation parameters: the principal distance *c*, the principal point coordinates x_0, y_0, three correction terms for radial distortion (K1, K2, K3) and two correction terms for decentering distortion (P1, P2). The mathematical basis of the calibrating process is the collinearity model reported in Eq. (1).

$$(x - x_0) + \Delta_x = -c\,\frac{U}{W}$$

$$(y - y_0) + \Delta_y = -c\,\frac{V}{W} \quad (1)$$

with

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = R \begin{bmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{bmatrix}$$

Where X_0,Y_0,Z_0 individuate the perspective center in the world coordinate system and R is the rotation matrix. The formulas in Eq. (1) are used to relate the 3D coordinates of the points in the world coordinate system X, Y, Z, with 2D coordinate in the image coordinate system x, y, z (Fig. 2). Both coordinate systems are related to each other by internal orientation parameters (characteristics of the camera), and external orientation parameters (the position of the camera in the two reference systems). The terms Δx and Δy, are the image coordinate perturbation terms. The lens distortions compensation is realized by applying Eq.(2).

$$x_c = x + dr_x + dp_x$$

$$y_c = y + dr_y + dp_y \quad (2)$$

The coordinates x_c, y_c locate the corrected image point respect to an origin positioned in the principal point; dr_x and dr_y, are the x and y component of the radial lens distortion correction and dp_x and dp_y, are the x and y component of the decentering lens distortion correction.

The radial lens distortion is radially symmetric respect to the principal point and it is calculated by applying Eq.(3).

$$dr_x = dr_y = dr = K1 \cdot r^2 + K2 \cdot r^4 + K3 \cdot r^6 \quad (3)$$

with

$$r = \sqrt{x^2 + y^2}$$

Decentering distortion is often not modelled b**e**cause its contribution is much smaller than radial lens distortion [14]. However, to achieve the highest accuracy measurements, decentering distortion has to be take into account.

$$dp_x = P1 \cdot (r^2 + 2 \cdot x^2) + 2 \cdot P2 \cdot x \cdot y$$

$$dp_y = P2 \cdot (r^2 + 2 \cdot y^2) + 2 \cdot P1 \cdot x \cdot y \quad (4)$$

The Eq. (4) shows the formulas used by PhotoModeler Scanner® 2010 for the decentring distortion compensation.

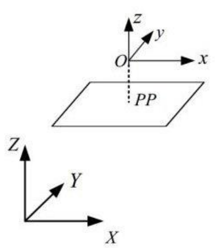

Fig. 2. Representation of the image and the world coordinate systems. The perspective centre and the principal point are denoted by O and PP respectively.

3.1. The Self Calibration

The procedure for self-calibrating a camera is based on the solution of a bundle-adjustment calculation, performed considering as unknowns the six external orientation parameters (X_0, Y_0, Z_0, ω, φ, κ) which identify the camera in the world coordinates system, and the internal orientation parameters of the camera (c, x_0, y_0, K1, K2, K3, P1, P2).

The algorithm of a SC is able to identify some known geometries in the images, that are called calibration grid (flat sheets on which there are four control points and a pattern of dot). Knowing the coordinates of a certain number of grid points, it is possible to solve the calculation of bundle-adjustment. The pictures were acquired and processed by PhotoModeler Scanner® 2010.

The results of the SC are not satisfactory, because the process generates a too simplified model. Since low-cost consumer cameras have been used, the poor quality of the lenses induces some distortions in the images, that cannot be modelled with a simple SC process. In fact, by applying the algorithm, the software fails to converge to a certain value, and set that particular parameter to zero. In this case, K1 is the only distortion parameter that the software was able to calculate, this means that the camera model is not able to compensate adequately the lens distortions.

3.2. The Full Field Calibration

The FFC process is able to build a model of the pair camera/optic by using a particular three-dimensional calibrator. For this purpose a modular solid 3D calibrator was realized (Fig. 3).

The peculiarity of this calibrator, compared to the flat sheets, is to have three levels of height, that allow to consider the 3rd dimension of the specimen during the calibration. The solved calibration parameters, are shown in Table 1.

According to the expectations, the FFC produced a very good model, which take into account the effects of radial distortion (K1 and K2) and decentering distortion (P1 and P2). In fact, except for K3, the software was able to calculate all the internal camera parameters. Thus, these models will enable to obtain more accurate results, than those achievable by implementing the models built with the SC process only.

Furthermore, since in photogrammetry the Residual is the measure of the maximum distance (in pixels) between where the point was marked on a photo and where the projection of the 3D point associated with that marked point falls on the photo, the Maximum Residual (MR, the largest residual across all marks in the project) and the Overall RMS (the average residual), represent relevant parameters for gauging the quality of the calibration. In Fig. 4 are shown the graphics related to the MR (a) and the Overall RMS (b), obtained with a SC (in blue) and with a FFC (in light blue), for each camera of the proposed scanning system. The red lines indicate

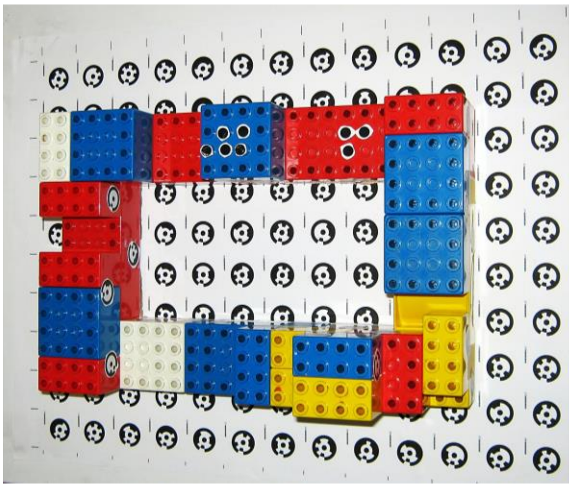

Fig. 3. Solid three-dimensional calibrator used for the FFC.

Table 1. Full Field Calibration Results.

# Cam	c [mm]	x_0 [mm]	y_0 [mm]	K1	K2	P1	P2
1	6.80	2.94	2.25	$2.26e^{-3}$	$-1.24e^{-5}$	$1.73e^{-5}$	$3.69e^{-5}$
2	6.78	2.88	2.29	$2.50e^{-3}$	$-2.32e^{-5}$	$-1.00e^{-5}$	$5.01e^{-5}$
3	6.80	2.96	2.31	$2.37e^{-3}$	$-1.55e^{-5}$	$1.17e^{-5}$	$3.89e^{-5}$
4	6.81	2.93	2.35	$2.42e^{-3}$	$-1.17e^{-5}$	$5.57e^{-6}$	$2.46e^{-5}$
5	6.82	2.89	2.30	$2.04e^{-3}$	$-7.26e^{-6}$	$1.02e^{-4}$	$9.19e^{-5}$
6	6.81	2.93	2.31	$2.51e^{-3}$	$-1.90e^{-5}$	$7.69e^{-5}$	$6.07e^{-5}$
7	6.81	2.90	2.18	$2.45e^{-3}$	$-4.58e^{-7}$	$-6.76e^{-5}$	$9.88e^{-6}$
8	6.81	2.92	2.17	$2.30e^{-3}$	$-1.29e^{-5}$	$3.42e^{-6}$	$2.29e^{-5}$

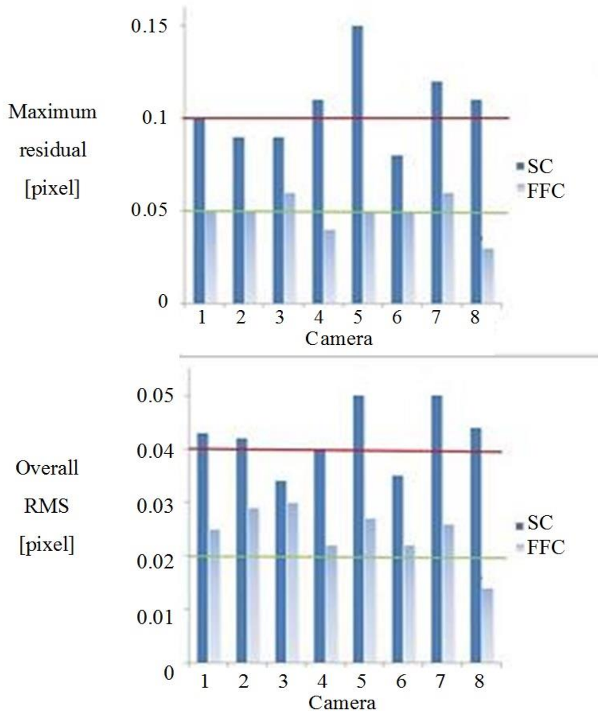

Fig. 4. (a) MR comparison; (b) Overall RMS comparison.

the average values achieved with the SC, while the green lines indicate the average values achieved with the FFC. As is clearly apparent, with the FFC it was possible to reduce the average value of both parameters, MR and Overall RMS, of about 50%.

4. Results and discussion

With the aim to ascertain the suitability of the proposed scanning system to medical diagnostic application, a real human body was scanned. In Fig. 5 are reported the pictures acquired and used to build the 3D model; the remote control allowed to take them simultaneously. The images were then sent wirelessly to the computer. The simultaneity of the shots is very important, in order to eliminate the errors related to the subject's involuntary movements. The modeling process was carried out with PhotoModeler Scanner® 2010, which oriented the cameras and processed the images. In Fig. 6 are reported the point cloud and the textured dense surface. Among all the parameters calculated by PhotoModeler Scanner®, the Maximum Residual (MR) and the Final Total Error (FTE), are relevant internal quality measures, useful to gauging the quality of the 3D model. As already explained above, the MR is the largest residual across all marks in the project and it should be less than 0.5 pixel [11], while the FTE is a statistical parameter calculated in bundle adjustment, that measures how well all the input data (camera parameters, mark locations, and 3D points) agree with each other, and it should be under 1.0. For the model in Fig. 6 the MR is 0.18 pixels, while the FTE is 0.87. In order to perform an evaluation of the quality of the model obtained, the proposed scanning system was also used to scan a static subject. The MR and the FTE measured for the 3D model of a mannequin are very close to these obtained for the 3D model in Fig. 6 (0.21 pixel and 0.90 respectively). Furthermore, it was also analyzed the Mean Internal Error, estimated by

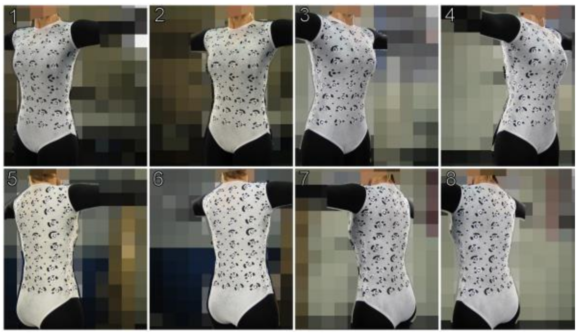

Fig. 6. Pictures used to build the 3D model of the human body. The number reported in each photo, refers to the number of the camera which taken it.

Fig. 7. The point cloud and the textured dense surface of the human body's model.

PhotoModeler Scanner® 2010 in term of point spatial position, for 60 coded targets attached on the observed specimen. The precision is 0.05 ± 0.01mm for a static subject, and 0.07 ± 0.01mm for a non-static subject. Because of photogrammetry is for the most part not dependent on scale (the smaller the object the smaller would be the error in absolute terms), the precision was also calculated as "1 in NNN" type numbers. The scanned human body is about 600 mm long; therefore the precision is 1:9'000 (1 part in 9'000), and thus, according to the Photomodeler classification, it was achieved a good accuracy level [12].

Internal quality measures supplied by PhotoModeler Scanner® 2010 help to determine the quality of the model, anyway these cannot ascertain the accuracy of the scanning system in absolute. A true accuracy check should be done with reference to an external data source, such as laser trackers, laser scanners, coordinate measuring machines, and others [15]. For this work, the laser scanner Konica Minolta Vivid 910 was used.

In Fig. 7 is reported the result of the 3D comparison, carried out by comparing the models of the dummy scanned with both, the laser scanning Konica Minolta Vivid 910 and the proposed scanning system. The

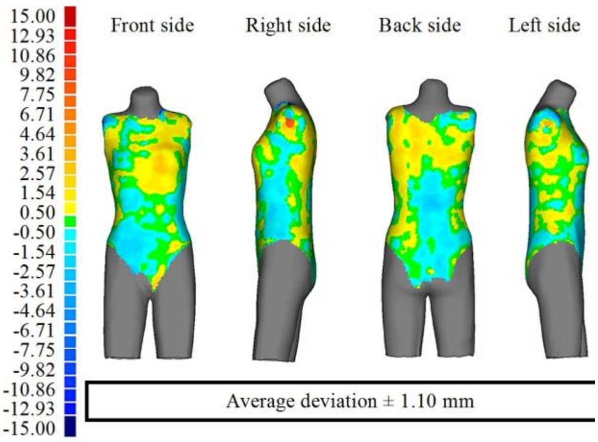

Fig. 5. 3D Comparison between the dummy's models realized with laser scanner Konica Minolta Vivid 910 and the proposed body scanning system (scale in mm).

overall 3D average deviation measured between the two models is ±1.10 mm. The comparison was carried out considering only the models of the dummy because of the difficulty to realize a complete (360 degrees) in-vivo scan with the laser scanner. In fact the laser scanner presents some problematic factors such as the long acquisition time, and the need to rotate the subject with the aim to obtain a whole 360° model.

In both cases, the subject would certainly change the pose during the scan.

5. Conclusions

In this work a performing and low-cost body scanning system based on close-range photogrammetry was presented. With the aim to verify the suitability of the system for medical diagnostic application on human body, several parameters have been considered. The analysis of some internal quality measures calculated by PhotoModeler Scanner®, allowed to state that the system is able to perform precise 360° models, for both applications, static and non-static subjects. The accuracy was evaluated using an external measurement tool, with a certified accuracy: Konica Minolta Vivid 910 (accuracy of ±0.29mm for static subject applications). The 3D comparison of the models obtained by scanning a dummy with both technologies, allowed to highlight further advantages of the proposed body scanning system in application on human body, respect to a laser scanner system. First, the short scan time: in fine mode Konica Minolta Vivid 910 is able to capture 307'200 points in 2.5s [16] that is very good, but is not fast enough to avoid the problems related to the subjects' involuntary movements. However, the duration of the acquisition can be reduced by using Konica Minolta Vivid 910 in fast mode, lowering the scan accuracy. Second, the possibility to obtain a complete in vivo scan, in a single scan session. In fact, to obtain a 360° model with the laser scanner, four scan sessions are required. This means that the subject have to rotate of 45 degree for each session. Since the human body is not as rigid as the dummy, during the rotation he would certainly move from his initial position, introducing some errors in the model. The alignment and the manual registration of the point clouds, needed for multiple laser scans, would introduce further errors, and the model would resulting low in accuracy.

In conclusion, the proposed body scanning system has proved to be cheap, reliable and accurate. It is non-invasive, and results competitive compared to other scanning systems, such as laser scanner, in term of cost of the equipment and accuracy, for applications on human body such as post-operative evaluation of surgeries or to make custom medical devices.

References

[1] Kuo, C.F., Wang, M.J., 2009. Motion generation from MTM semantics, Computers in Industry 60, pp. 339–348.

[2] De Donno, A., Carlucci, D., Introna, F., 2008. The use of infrared rays for identification purposes, Journal of Forensic Identification, pp. 193-202.

[3] Galantucci, L.M., Percoco, G., Angelelli, G., Lopez, C., Introna, F., Liuzzi, C., De Donno, A., 2006. Reverse engineering techniques applied to a human skull, for CAD 3D reconstruction and physical replication by rapid prototyping, Journal of Medical Engineering & Technology 30, pp. 102-11.

[4] Fourie, Z., Damstra, J., Gerrits, P. O., Ren, Y., 2011. Evaluation of anthropometric accuracy and reliability using different three-dimensional scanning systems, Forensic Science International 207, pp. 127-134.

[5] Jones, P., Rioux, M., 1997. Three-dimensional surface anthropometry: Applications to the human body, Optics and Lasers in Engineering 28, pp. 89-117.

[6] Chang, C., Dempsey, P. G., Cai , X., Li, Z., 2008. Refraction effect analysis of using a hand-held laser scanner with glass support for 3D anthropometric measurement of the hand: A theoretical study, Measurement 41, pp. 842-850.

[7] Galantucci, L.M., Percoco, G., Dal Maso, U., 2008. Coded targets and hybrid grids for photogrammetric 3D digitisation of human faces, Virtual and Physical Prototyping 3, Vol. 3, Issue 3, pp. 167–176.

[8] Galantucci, L.M., 2010. New challenges for reverse engineering in facial treatments: How can the new 3D non-invasive surface measures support diagnoses and cures?, Virtual and Physical Prototyping 5, pp. 3-12.

[9] Deli, R., Di Gioia, E., Galantucci, L.M., Percoco, G., 2011. Accurate Facial Morphologic Measurements Using a 3-Camera Photogrammetric Method, Journal of Craniofacial Surgery 22, pp. 54-59.

[10] Hwang, S. 2001. Three dimensional body scanning systems with potential for use in the apparel industry, Doctoral dissertation, North Carolina State University.

[11] Percoco, G., 2011. Digital close range photogrammetry for 3D body scanning for custom-made garments, The Photogrammetric Record 26, pp. 73-90.

[12] http://www.photomodeler.com/kb/entry/63/

[13] Brown, D.C., 1971. Close-Range Camera Calibration, Photogrammetric Engineering, pp. 855-866.

[14] Remondino, F., Fraser, C.S., 2006. Digital camera calibration methods: consideration and comparisons, International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 36, pp. 266-272.

[15] Galantucci, L.M., Lavecchia, F., Percoco, G., Raspatelli, S., 2014. New method to calibrate and validate a high-resolution 3D scanner, based on photogrammetry, Precision Engineering 38, pp.279–291

[16] http://www.upc.edu/pct/documents_equipament/d_288_id-715.pdf