Stereo Photogrammetry vs Computed Tomography for 3D Medical Measurements

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Abstract

The acquisition of 3D body measurements by computer vision-based remote sensing is becoming extremely substantial in clinical studies nowadays. Thus, accurate 3D models of human anatomical surfaces are required in many clinical routines like disease diagnosis, patient follow-up, surgical planning, computer assisted surgery and different biomechanical applications. These models can be generated from different imaging techniques such as computed tomography (CT). However, 3D conventional medical imaging like CT scan have serious limitations in application such as exposing the patient to ionizing radiation due to repeated scans, highly cost imaging process, failure to provide color texture information, and also lacking to apply the process in standing position. Recently 3D model reconstruction using stereo-photogrammetry have been taken into consideration as a reliable alternative technique to CT scan. This is particularly true because photogrammetry can achieve accurate 3D models with low cost and high accuracy results and further considered a non-invasiveness and non-irradiating technique if compared to CT imaging. In this paper, 3D digital models generated by close range photogrammetry (CRP), is investigated for validation against CT scan models (Stereo-Lithography (STL)) which expressed as gold standard models. This is particularly applied to propose using CRP as an alternative non-irradiated solution to X-ray radiated imaging to provide accurate 3D measurements for plastic surgery treatment in certain medical cases. Two 3D plastic models used as test objects in this research and therefore scanned by CT scan device and hand-held digital camera. The accuracy assessment was carried out using cloud-to-mesh (C2M) function followed by co-registration process between each pair of 3D corresponding surfaces. The C2M deviation distances computed and analyzed for all tested models. The RMSE values for deviation distances between individual pairs of 3D corresponding surfaces were found to be several parts from millimeter in both tested objects. Statistical analysis was also applied which shows no significant differences between both compared generated models. Validation measurements of specific regions within the models were carried out by computing the relative difference between both techniques which found to be clinically adequate and medically accepted for application.

Keywords

Photogrammetry, Computed Tomography, Medical, SfM, 3D modeling.

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1. Introduction and literature review

The latest fast development in computers made the acquisition, recording and processing of 3D digital images technically easier [1]. Nowadays, 3D models are used in extensive variety of application areas [2]. The medical industry uses detailed models of organs for illustration, diagnosing, and surgical applications [3,4]. 3D modeling of scenes and objects is an intensive and extensive research problem in computer vision, graphics, and photogrammetric communities [5]. Nowadays, 3D modeling is a significant issue in medical studies for diagnosis and treatment of pathologies. They used more widely for morphometric studies and operation planning [6]. The common techniques used for delivering 3D digital models of human anatomical surfaces are: computed tomography (CT), magnetic resonance imaging (MRI), laser scanner, structured light technique, and close-range photogrammetric (CRP) approaches [7]. Number of these procedures are considered invasive, expensive, irradiated, do not provide color texture information about surface, and cannot be applied in standing positions. Currently, the use of CRP for creating digital 3D surface models has been taken into consideration widely as a reliable alternative. This is due to the fact that CRP offering several advantages such as: low cost (where only simple tools are required such as lighting tools, digital cameras, and appropriate rendering software), non-irradiated, accuracy, color texture information, and also ability of being applied in standing positions [6].

Since the beginning of photogrammetry, a number of photogrammetric studies has directed the research potential of photogrammetry towards medical measurements in different studies. CRP techniques used in different medical applications: (i) Dermatology where photogrammetry is used to provide accurate measurements of wounds, but an important challenge lies in providing simple and cheap technique to be utilized in clinics outside hospitals [8]. Therefore, many studies have focused on the use of low-cost photogrammetry for wound measurements treatment. In this respect [9] assessed 3D digital surface modeling of skin wounds by using Zephyr 3D industrial scanner system and recommended for application. (ii) Teeth and jaw where CRP used in dentistry to create accurate dental models for study bite contact in the teeth and jaw [10]. CRP proved to be effective in observing normal and

abnormal growth, surgical planning, malformations and assessment of therapy in orthodontic surgery [11]. For validation purposes [12], investigate the reliability of using CRP to create 3D models of orthodontic plaster casts by using calliper measurements as a gold standard for comparison which delivers promising outcomes. (iii) Face where CRP measurements utilized on the face more than any other parts of the human body. Measurements made to monitor the facial shape as it changes over an extended period of time, through growth [13] and during the treatment of different conditions [14,15]. (iv) Other applications where CRP used to model and measure many other parts of the body such as spine [16], prostheses design [17], breasts [18]. Recently, CRP used to create digital interactive models of cadaver specimens that can be used for anatomical education. These models are accurate, more detailed and provide more visual spatial information than 2D images [19]. In addition, photogrammetric approaches can be used to create digital libraries of 3D anatomical samples. These libraries would be valuable in institutions and regions that lack cadavers and can serve as helpful educational supplements [19]. Many studies assess the accuracy of digital 3D surface models against linear and angular measurements generated by tools such as calipers and commercial optical scanners. However, very little work has presented and discussed the accuracy assessment of the digital low cost photogrammetric model against a model produced from very best clinically tool like CT. In this research, 3D modeling using photogrammetric technique for medical applications was presented and discussed. This was applied by a computed tomography (CT) scanning process as a reference for comparison and validation with CRP. CRP was presented as an alternative low-cost solution for diagnosing and surgical operations in plastic surgery and multiple medical treatment.

2. Testing objects

CT scanner imaging technology would expose any human object to harmful radiation. So if a real human participant was imaged to deliver real data for this research, ethics would have necessary to be considered. Therefore, two plastic models (mannequin head and hand) used as alternative testing surfaces instead of a real human body. The mannequin head was chosen to be the surface of choice in the second test because it

has a difficult region to reconstruct using the photogrammetric technique, especially details of the mannequin ear and nose. It worth mentioning that CRP photo session was applied in middle technical university laboratory whereas the CT scanning session was applied in Baghdad Teaching Hospital, Iraq.

3. Methodology

3.1. Close-range photogrammetry (CRP)

Since the two objects (hand and mannequin head) in this research have smooth surfaces and homogenous look, determining corresponding points on images becomes very difficult in photogrammetry. Therefore, black paint texture was applied to mannequin head, and 14 circular coded targets were placed on the hand as shown in Fig. 1. This was applied to improve the detection of corresponding points on overlapped images in stereo CRP. Further, small plastic pins with 0.5 mm radius and green industrial tape were used to select regions on the mannequin head and hand respectively [8]. These materials allowed certain regions to be specified on the models in two different modality data (CRP and CT) in order to validate the accuracy of area measurements.

Digital hand-held Nikon D5200 camera (AF Nikkor 18–55 mm zoom lens) was used to capture the images of the two objects. Images captured in natural light conditions to produce better resolution, evenly colored, and realistic textured images without shadow. The images did not capture in a 360° ground coverage because this scenario may waste time to be processed and further there was no need to cover the back side of both objects in this study. Therefore, the 3D model of single faces for each object was used. The objects' faces were imaged from different angles. The minimum overlap between images was 80% to avoid gaps resultant in the reconstructed models. The focal length was kept constant during the entire image session in order to keep the IOP of the camera stable as much as possible. The properties of the image acquisition sessions are highlighted in Table 1.

For the 3D reconstruction process, *PhotoScan* commercial software based on structure from motion (SfM) and multi-view stereo (MVS) approach was used. The software was selected to process the data in this research because of its high level of automation in image processing in addition to its high analysis performance. SfM detected corresponding points between the overlapping images and create a descriptor for all these points through SIFT algorithm [20]. This deliver

a list of corresponding points those representing sparse point clouds. These corresponding points were also employed for the estimation of interior and exterior orientation parameters of the camera based on a bundle-adjustment algorithm [21]. The sparse point clouds and the camera parameters generated from SIFT and bundle-adjustment were employed to generate the final dense point clouds by applying MVS algorithm (Fig. 2). It is worth to mention that all processing steps are applied to high-quality parameters.

3.2. CT scan data

Since CT scan data is considered to be ground truth (gold standard) data in this research, its accuracy level is an essential issue. In this research, the accuracy and resolution of CT data is mainly depending on the accuracy of the CT scanner device and scanning parameters used, which represents the pixel spacing and the slice thickness. Generally, in CT scanning, 3D volumetric data is offered as axial image slices with a specific user-defined thickness [21]. A single image slice is consisting of a 2D array of elements called "pixels" in addition to the thickness. These 3D information elements unite to be called "voxels". The voxel is basically the intensity or average signal of the tissues that represent it [22]. The voxel size is determined by the slice thickness, size of the image matrix, and the sensor field of view (FOV). In order to gain an accurate representation of the scanned anatomical structures, a voxel size should be small enough. When the size of the voxel becomes larger, it may accumulate the average attenuation/signal from more tissue types and deliver a larger tissue volume. Thus, larger voxel size (low resolution) leads to higher inaccuracies in 3D extracted models due to inadequate representation of the anatomical structures [22]. Therefore, in this work in order to obtain high accuracy, CT scan data was captured with small voxel size (Table 2 is highlighting the CT scan data settings) to deliver high accuracy models.

Following CT data acquisition, CT images are recorded in DICOM format. In DICOM files, the detailed information about the scanning parameters is recorded and saved. For example, pixel size on x and y directions, slice thickness, scanning direction, scanning type, etc. In this work, *3D slicer* software is utilized for 3D reconstruction from CT data. After loading DICOM data into *3D slicer*, the segmentation process is performed, which is the first step in mesh generation from CT data. The ROI boundaries are distinguished on all image slices through the visual selection of the threshold value. This was commonly achieved by

Fig. 1. Research case studies: Hand with the coded target (left) and mannequin head with black paint texture and coded targets in the background (right).

setting a threshold level that reasonably determines the ROI without over or under estimation. It was noticed that delivering some noise data with segmented ROI is unavoidable. Thus, the noise data was removed by using scissor tool in *3D slicer* software. After careful segmentation process, 3D surface generation applied. This process was performed automatically by utilizing marching cube algorithm [23]. Finally, the 3D surface model was saved as a stereo-lithography (STL) format. The model extracted from *3D slicer* has a pixelated look. Thus, smoothing filter was applied using *Blender* software (open source software) to remove the noise (pixelated look) in the generated mesh models, see Fig. 3.

3.3. Cleaning 3D models

In this step, thickness data and unnecessary faces in STL models are removed using *Meshlab* (open source) software. This was achieved by selecting visible faces only and as shown in Fig. 4. Later, the models of the selected faces are exported as new layer. Thereafter, in *cloud compare* software the unnecessary regions in the

left and right face of the mannequin head was removed from photogrammetric and corresponding STL models using manual segmentation tool (Fig. 5).

3.4. Accuracy assessment

The procedure used to test the accuracy and feasibility of low cost CRP approach against CT scan approach, comprises of 3D surface comparison and statistical analysis.

3.4.1. 3D surfaces comparison

Comparison between two clouds requires both clouds to be in the same reference coordinate system. Thus, co-registration (alignment) procedure was applied. The main approaches applied for alignment tasks are: first, alignment by picking at least four point pairs in both clouds (rough registration); and second, the Iterative Closest Point (ICP) (fine registration) [24]. ICP has been much used in co-registration because of its strength and good performance especially when the two datasets overlapped in a large extent and have small differences [25]. In this work, individual

Table 1
The properties of image acquisition session in CRP technique.

Object	Camera-object distance (m)	Focal length (mm)	Scale	Number of photos	GSD (mm)
Hand	0.5	38	1:13	60	0.05
The frontal face of mannequin head	1	45	1:22	53	0.09
Left part of mannequin head	0.5	55	1:9	33	0.03
Right part of mannequin head	0.5	55	1:9	33	0.03

Fig. 2. Dense point clouds generation using CRP, (a) frontal face of mannequin head, (b) left part of mannequin head, (c) right part of mannequin head and (d) the hand.

photogrammetric models aligned in the same coordinate system with the corresponding CT model. First, by using alignment (point pair picking) tool, which used few selected points for alignment and later the total RMSE is computed. Second, improve the alignment process (minimize RMSE value) by applying fine registration (ICP tool) to align point cloud generated from first alignment step with corresponding STL model (model vertices). The delivered RMSE value by the ICP tool is computed on up to 50 000 points ('random sampling' parameter). The theoretical overlap between each point cloud and the corresponding

STL model (selected mesh vertices) is set to 90% for all objects. Following alignment step, 3D surfaces comparison is carried out to compare photogrammetric point cloud model against mesh model generated from CT data (gold standard model). The two clouds are compared using cloud to mesh (C2M) tool in *cloud compare* software. The C2M function calculates the distances between every point and the nearest triangle of the 3D mesh data. In the situations where the orthogonal projection of the point lies within the triangle, the distance between the point and its intersection point on the triangle is computed. Otherwise, the

Table 2

The characteristics of the CT scan data.

	Object	Image resolution	Pixel spacing	Slice thickness	Number of images
CT Philips Bireliance 364 slice	Mannequin head	768 × 768	0.3255	0.3299	773
	Hand	768 × 768	0.2252	0.3299	413

Fig. 3. The generated CT mesh model, the mannequin head (left) and the hand (right).

cloud compare software calculates the distances between the point and its projection to the nearest edge of the triangle [26]. The absolute re-construction accuracy of the 3D surface comparison is assessed by calculating the RMSE value.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n D^2}{N}} \quad (1)$$

where: RMSE is the root mean square error; D is the residual distance between point in 3D space and its

Fig. 4. The selected faces in *Meshlab* software; (a) Hand, and (b) mannequin head.

Fig. 5. Manual segmentation regions (green-outlined polygon); photogrammetric model (right) and corresponding STL model (left).

nearest triangle in mesh data; and N is the number of points.

3.4.2. Statistical analysis

Statistical analysis was carried out to investigate the agreement between the two techniques (CRP and CT scan). Two-sample T-test was applied to achieve this by analyzing whether the mean of the two samples is significantly different or not. This was applied using *Minitab* professional statistical software. Due to the limitation of *Minitab 18* to process large data samples, selected areas on the mannequin head and Hand are only analyzed in this procedure.

3.5. Validating surface area measurements

To validate the accuracy of the generated surface area, several regions are selected (polygon on the hand, left and right ear and nose on the mannequin head). A relative difference was computed for each surface area from CRP models with respect to the corresponding surface area from STL model (mesh). The surface area of the selected regions was calculated using *cloud compare* software. To calculate the surface area for the selected regions on both point cloud and mesh data models, first, the selected regions are segmented using scissor tool. Second, surface area of the segmented point clouds was calculated using fit facet tool in *cloud compare*. This was applied by fitting the point cloud to a tessellated polygon (this only applied for 2.5D clouds). Thus, the points are equivalent to a mesh, and the surface area is simply the sum of the triangles

areas. Further, the surface area of the corresponding mesh model was calculated using measure surface tool in *cloud compare* software through the total sum of the triangles areas. Finally, the relative differences of the surface area measurements for segmented regions have been calculated as follows:

$$\text{Relative difference} = \frac{b - a}{a} \quad (2)$$

where: b is the surface area measured for segmented polygon on point cloud generated by CRP, and a is the surface area measured for the corresponding segmented polygon on STL model.

4. Results and discussion

4.1. Cloud to cloud comparison

As a result of C2M comparison, the deviation distances between the two analyzed models are represented in color map to show difference values closely (Fig. 6).

As shown in Fig. 6, positive values mean that points in CRP models lie above the reference surface (CT model). Whereas, negative values indicate that points are below the reference surface. In addition, it is easy to note that the areas with green colors representing high accuracy areas. Fig. 6(d) shows that the hand model has a complete virtual consistency with the compared surface (CT model). However, Fig. 6(a–c) shows that the mannequin head models have some areas with large deviation illustrated in red color. This

Fig. 6. Color map of 3D surface differences between CT and CRP models in mm; (a) left part of the mannequin head (b) right part of the mannequin head, (c) frontal face of the mannequin head, and (d) the hand.

is mainly because the added texture in mannequin head was less reflectance from surroundings and thus due to the reason that the surface is made from a slightly reflective material. This negative indicator affects the alignment results and therefore dense point cloud have noisy points in this particular object. Further, it is easy to note that hair regions on the mannequin head has more texture and represent high accuracy regions. After computing C2M distances (errors), the histograms of the resulted errors are simulated to represent the distribution according to normal distribution curve as shown in Fig. 7. In addition, the mean, standard deviation and RMSE are computed for C2M deviations as illustrated in Table 3.

As shown in Fig. 7, the histograms of C2M differences between CRP point clouds model and the corresponding CT model indicates that the distance distribution in Fig. 7(a–d) is different where the

average C2M distances are always close to zero. The standard deviation is the most meaningful statistical indicator which delivers information on how well each part matches - the narrower shape is always better as it means closeness to the mean value with low residual values. The figure shows that the standard deviation for the frontal face of the mannequin head are greater than the standard deviation of all other models. Further, it is easy to note that 95% of the points have errors less than ± 0.228597 mm for hand, ± 0.325465 mm, for frontal face of the mannequin head, ± 0.110188 mm for left part of the mannequin head, and ± 0.170750 mm for the right part of the mannequin head. Also in Table 3 it is easy to note that the RMSE for the frontal face of the mannequin head are greater than the RMSE of all other models. This concludes that the 3D model of the frontal face of the mannequin head have some noisy points. These results between the two techniques

Fig. 7. Histograms of C2M differences for the 3D surface comparison test.

indicate that the CRP data is accurate but slightly different from the corresponding CT data and therefore needs further analysis. Following these findings, these results are statistically analyzed to investigate whether the differences between the two techniques are significant or not.

4.2. Statistical results

Statistical analysis was performed in this research to test the hypotheses if the two techniques are significantly different or not. Each of the two corresponding 3D point clouds models generated for individual object was tested to investigate the agreement between the two techniques. The first step was to check the normality of the entire data. The normality test was applied using 95% confidence interval (CI) level. As a result, the p-value with less than 5% means that the

null hypothesis should be rejected which approved that the data are normally distributed. When the normality test was performed, it was found that no follow to the normality never exists, as the p-value is less than 5% as shown in Fig. 8.

In such cases, statisticians recommended to use non-parametric tests to normalize data values.

Table 3

Descriptive statistics of C2M differences between two tested techniques.

Object	Mean (mm)	Std.(mm)	RMSE (mm)
Hand	0.015481	0.151874	0.152661
Frontal face of mannequin head	0.009792	0.242625	0.242822
Left part of mannequin head	0.001272	0.109631	0.109638
Right part of mannequin head	0.002784	0.126797	0.126828

Fig. 8. Normality test of the mannequin head (CRP point cloud model).

Fig. 9. Levene's test details of the hand model, interval plot (left) and box plot (right).

However, because the size of individual samples is large enough (more than 100 000), the normality checking of the data was not an issue. This is mainly because the non-normally distributed data could be well manipulated if the sample size is large enough and the two-sample T-test is used for analysis. Statistical analysis was applied in the X, Y, and Z, value differences for the two corresponding surfaces. The two-sample T-test was applied using 95% CI interval, which means the p-value with less than 5% should accept the hypothesis and approved the two techniques

are significantly different. However, the T-test cannot be performed without variance analysis of both examined samples individually. Testing the variances delivers p-value from two-independent hypotheses, Levene's and F-tests. Levene's test should be adopted when the data are not normally distributed which was the case. Whereas, F-test should be performed when the data are normally distributed. The Levene's test conclude the hypotheses of equal variances. Fig. 9 shows the results from testing variances in y-axis for frontal face of the mannequin head.

Table 4
Statistical analysis results of two-sample T-test for all tested objects.

Object	Dataset	P-value	T-value	Estimate for diff. in mm	95% CI for diff.
The hand	X	0.357	0.92	0.0273	−0.0853, 0.0308
	Y	0.000	4.23	0.0562	0.0320, 0.0823
	Z	0.473	−0.72	−0.0197	−0.0737, 0.0342
Frontal part of mannequin	X	0.763	−0.30	−0.0097	−0.0727, 0.0533
	Y	0.009	−2.61	−0.0591	−0.1036, −0.0146
	Z	0.246	−1.16	−0.0568	−0.1527, 0.0392
Left part of mannequin	X	0.000	8.05	0.06343	0.04799, 0.07888
	Y	0.000	−27.47	−0.4164	−0.4461, −0.3867
	Z	0.000	−9.02	−0.2271	−0.2764, −0.1777
Right part of mannequin	X	0.000	7.82	0.05863	0.04394, 0.07332
	Y	0.000	−38.67	−0.5946	−0.6247, −0.5645
	Z	0.000	−5.95	−0.1559	−0.2072, −0.1045

Table 5
Area validation measurements in mm and relative difference of measured area.

Segmented object	Point cloud surface area (mm)	Mesh surface area (mm)	Relative difference (mm)
Ear left	1531.23	1833.07	−0.1646
Ear right	1550.57	1876.99	−0.1739
nose	964.175	1644.16	−0.4135
Hand	896.108	899.16	−0.0033

The p-value for x, and y samples of the left part of the mannequin face was found to be more than 5%, therefore, we accept the null hypothesis of equal variances for these two samples. However, the p-value for the other samples were less than 5%, thus, we reject the null hypothesis of equal variances for these samples. These results are used later as input to the two-sample T-test.

The two sample T-test statistical analysis report is illustrated in Table 4. The estimated difference between the means of the two corresponding models is lying within the confidence interval. This indicates that the two models are not significantly different. In addition, the results of the p-value in Table 4 for some samples are equal to zero and these values are difficult to interpret in such cases. Therefore, T-value are analyzed to investigate the difference between any corresponding models from the comparative techniques. T-values in Table 4 shows that there is a non-significant difference between any two corresponding samples. Also from Table 4 it is easy to note that the accurate model is the model of the hand that processed with the supplementary of coded targets.

4.3. Area validation measurements

The validation of area measurements and the relative difference of the segmented parts of the two 3D corresponding surfaces are shown in Table 5 below.

From Table 5 it can be seen that the relative differences of the measured area of the selected polygons from the mannequin hand have a higher accuracy than other surface area measurements. This may be due to noise and small gaps in point clouds model of the mannequin head. Generally, the relative comparison of surface area measurements showed that there is no significant difference is detected between the two techniques. This means that photogrammetric technique is clinically adequate and medically accepted to be used as an alternative to CT scan approach for plastic surgery and related medical treatment.

5. Conclusions

This paper is presenting a methodology to use the non-irradiated CRP technique as an alternative 3D measurement approach to X-ray imaging in order to provide accurate measurements for diagnosing diseases and surgical treatment in medical field. 3D digital models are generated by stereo CRP and investigated for validation against CT scan (STL) models where the later are considered to be gold standard models. The results showed that the dense point clouds generated by CRP is accurate and slightly different from the corresponding CT. The statistical analysis was found to be agreed with the visual analysis and findings. However, the validation process of area measurements on stereo CRP point cloud models against CT model showed no

significant differences between both techniques which are clinically adequate. From the results of this work it was proved that the non-invasive CRP technique is accurate enough and recommended to be used as an alternative solution to X-ray imaging to provide 3D information in some medical cases like plastic surgery and disease diagnosing such as scoliosis and skull deformity in children. It is also more desired, by both the clinics and public as a non-irradiative solution in such cases. For future works it is recommended to apply the methodology on patient case by employing a network of cameras to capture CRP images before clinical use. It is also recommended to employ multiple scanners like laser light scanner, MRI and commercial safe scanners and study differences from multiple sensors. Finally, it is of highly importance to use CRP to create database of 3D anatomy models to be used as tools in anatomical education in Iraq.

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