Teeth Model Reconstruction Based on Multiple View Image Capture

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Abstract. Various dentistry fields such as teeth treatment, dental restoration, and denture production require the application of three-dimensional intraoral scanners to create digital impressions. This study presents a method to reconstruct a three-dimensional teeth crown by utilizing a prototype intraoral custom design with publicly available software. The system consists of custom containing an endoscope camera and two light sources (white LED and blue laser), a personal control computer, and photogrammetric open source software packages (VisualSFM, CMVS/PMVS, and MeshLab). Photogrammetry methods were used to acquire the three-dimensional teeth model with high precision. Multi images have been captured of the interesting teeth using the custom system from different angles. The capturing process was done in two phases using one illumination source each time. The captured images are loading to Photogrammetry software to generate the three-dimensional dense point cloud. A comparison has been made of the resulted dense point cloud at each phase. Finally, the dense point cloud is loading to MeshLab software to generate the three-dimensional mesh that can be utilized in CAD/CAM software. The results have shown the superiority of using blue illumination with the photogrammetry software that shows good accuracy of teeth crown details and measurements that are related to the reconstruction algorithm which yields in more number of 3D points of the object to generate good three-dimensional meshes of the teeth crown. This study helps to offer low cost, simple design, and a user-friendly system to generate a three-dimensional teeth crown.

Keywords: 3D reconstruction, Teeth reconstruction, Photogrammetry, Laser, Intraoral camera.
1. Introduction

Computer vision is a field that includes methods for recognizing, processing, analyzing, and understanding images. It is known as image analysis or scene analysis. It imitates the capability of human vision by the means of electronically recognizing and analyzing the image. Through the computer vision, image data can be processed in abundant forms like video sequences, depth images, images captured from several cameras, medical scanner, satellite sensors etc. Three-dimensional (3D) reconstruction is a significant application of computer vision [1].

Three-dimensional reconstruction is a rife expression of multiple processes that target obtaining 3D information of scanned objects. This 3D image-based method processes utilize two dimensional cameras to obtain the 3D reconstruction. The 3D reconstruction methods can be divided into active and passive methods [2].

Active methods, also called range data methods, give the depth-map and reconstruct the 3D profile either by controlling the illumination of the scene like Kinect or via measuring the return time and phase shift of reflected waves like laser scanner [3]. These methods do not proceed effectively in sunlight or a poorly controlled environment. Generally, these methods are expensive and need the consultation of experts [4].

Passive methods determine the reflected rays emitted from the surface of objects, using a sensor to derive the 3D structure by image analysis. These methods are commonly based on multiple capturing of a certain object with a video camera or multiple cameras [5]. These methods can be utilized in wider fields compared with the active methods. In these methods light is used only for illumination and not in the reconstruction points’ triangulation which utilizing stereo algorithm to match the known similar points of image sequences [6].

Intraoral Digital Impression is a method that allows a dental professional to make a 3D reconstruction of a patient’s teeth, using lasers or other optical scanning devices and generate the image on a dedicated computer screen. Digital impression scanner can capture clear and highly accurate impression data very quickly, easier and more comfortable for both patients and dentist than the conventional impression methods [7]. Generally, intraoral scanners based on confocal technology need massive and expensive hardware. Most scanners devices used visible wavelengths rang (400-700 nm) since sound dental enamel has high light scattering, that prevent imaging through the tooth layers and improve the surface scanning process [8].

Over the century there has been many alternative options examined to improve digital tooth Impression methods and reduce its cost. In 2000 Sameh M. et. al. constructs a contact system for 3D model of patient’s jaw utilizing an intraoral video camera. Modified method of shape from shading (SFS) was used in the system. The suggested system used camera calibration and perspective projection to extracts the 3D data from a series of two dimension (2D) jaw images. Triangulation method utilized for solid 3D model reconstruction. The result showed acceptable reconstruction accuracy [9]. In 2016 Knyaz V. and Gabouchian A. utilize photogrammetric system to generate high resolution 3D dental models. The proposed system included two high resolution digital cameras, a high resolution structure light projector and computer to control the rotation position stage. Odontometric methods wad used on the final 3D model to estimate maximal teeth sizes in different dimensions [10]. Also, in 2017 Xiaoming F. et. al. discusses utilizing multi-baseline digital close-range photogrammetry (MBDCRP) method with single-lens reflex camera to reconstruct 3D orthodontic model of plaster cast. The result showed that MBDCRP with inexpensive hardware are alternative mode to save and scale dental models without requiring a special room to keep plaster casts [11].

In this study Photogrammetry process with inexpensive hardware are used to estimate the 3D coordinates of the teeth. photographs are used as the essential medium of measuring shapes and sizes by taking and analyzing images from multiple angles. The captured images are used as an input for a specialized software which search and match the visible 2D images features (a pixel) using the data collected from the camera’s positions and dimensions. The software output is 3D mesh of the teeth crown.
Initially, the total pipeline used to create the digital 3D teeth models is characterized. The pipeline displays the steps used in our experiment. First, the Structure from Motion software, called (VisualSFM), is used for images calibration estimation or cameras parameters, which will be saved as (.txt). The software also creates a 3D sparse point cloud that will be saved as (.PLY). The VisualSFM output is used as an input to the ‘Clustering Multi View Stereo’ (CMVS) software package to generate the 3D dense point cloud. Finally, MeshLab software is used to generate the teeth 3D mesh which could be exported to several 3D formats in compliance with the user’s requirements.

2. METHODS AND PROCEDURES

A. System outline

The proposed system is a computer-based system uses photogrammetric programs for 3D surface reconstruction of the teeth crown. As illustrated in Figure 1, the system consists of the following components:

Figure 1. Complete system structure

1. An intraoral custom designed using AutoCAD and solidwork software and printed using 3D printer to allow easy imaging access to the top and bottom teeth. It has a section of about 15 mm and length of 150 mm as illustrated in Figure 2.

Figure 2. Proposed intraoral custom design
2. A low-cost digital camera type (1800 endoscope) with resolution up to (1600x1200) pixels and can be manually adjusted in both lighting intensity and focus range as shown in Figure 3. A mirror at 45-degree angle is used for the horizontal viewing.

![Figure 3. Endoscope (model 1800)](image)

3. Two light sources
   a) Light emitting diode (LED).
   b) A blue diode laser with 405 nm wavelength and 5mW maximum output power. It is angled at 22 degrees horizontally to illuminate the teeth surface.

The capturing system can save images as JPEGs or any other format needed. The images are viewing and storing in the computer without the need for external storage devices. A USB power supply output cable connects each component to the computer. A suitable power level is used with the laser component to decrease the optical speckle noise and enhance the image contrast. The images are taken by positioning the intraoral system parallel to the teeth surface to illuminate the designated region.

B- 3D Imaging Using Photogrammetry Technologies

Photogrammetry is a passive process that estimates 3D coordinates of objects by using photographs as the essential medium of measuring shapes and sizes of objects by taking and analyzing images from multiple angles. Objects are measured with a remote-sensing technique [12]. In this study, 3D reconstruction of objects, observed by Photogrammetry Technologies made with Structure from Motion (SfM) method in which using a set of 2D images to produce 3D points cloud structure of an object. SfM methods are usually pipelined algorithms that each subtask processed sequentially. SfM commonly includes two phases; the correspondence phase which calculates the relations between geometrical input images through three sequential subtasks (feature extraction, feature matching and geometric verification), and the iterative incremental reconstruction phase which estimates the camera poses for each image and reconstruct the 3D sparse point cloud through three sequential subtasks (image registration, triangulation and bundle adjustment) [13].

detection processes based on searching for features points which define the object within the input picture such as corners, edges, interest points, ridges and etc. many methods used for detection process such as SIFT Algorithm that was used in this study to detect features and compare the images in the collection that produce a high number of correspondences and therefore good candidate for the SfM process.

After detection of the feature points, the next step was the matching process in which the keypoints acquired through feature extraction process are utilized to decide which images describe common parts of the object and are subsequently at least partially overlapping. In this study RANSAC Algorithm (RANdom SAmple Consensus) was used to automatic computation of F matrix during the geometry verification. RANSAC allows the calculation of the mathematical model parameters via random sampling. The algorithm based on that the data formed of inliers, which are the data of the model, and outliers, which represent the data that does not set to the model. When two keypoints in various images have the same description, consequently those keypoints can be considered to be the same in the object. The output of this step is a group of images overlapping minimally in pairs and groups of correspondences among features. After the matching process, the 3D points (comprise the 3D coordinate information of the relate points) were measured using the matching results; these were known as point
clouds. Triangulation method was used to predict a point location in the 3D space from its projections into two or more images to produce the sparse point cloud which performs the images and features that connect the images pair obtained from the geometrical verify.

Once the camera poses have been determining as sparse point cloud, the next process is to determine the surface of the object represented as a dense point clouds. This is an essential step to get a denser point cloud which is very useful for creating a precise 3D model with the objective of correcting occlusions in the object facets. The integration of SfM and MVS methods submit an automated workflow for the production of high-precision 3D dense point cloud [14]. Clustering Views for multi view stereo (CMVS) algorithm using the camera parameters and the 3D sparse point cloud resulting from VisualSFM as input data and then applying MVS process by grouping images with similar views to enhance determination performance. Patch-based Multi-View Stereo (PMVS) algorithm used to produce extra cloud points in to the 3D model based on the groups images specified via CMVS algorithm.

Due to the limited field of view, the prior step of 3D reconstruction does not produce the information for the proximal contact area between the adjusting teeth. So the reconstructed 3D view is incomplete. In this study, the Iterative Closest Point algorithm was used to merge two partial 3D models with applying the rotation matrix and the translation vector to the data set to get a full 3D view of the model [15]. Finally, using the 3D dense point cloud to create the 3D mesh by used the free MeshLab software.

C. Teeth 3D model generation software pipeline

After obtaining informed consent, a volunteer was a participant in the middle age of 25 from the patient population. Overhead lights were turned off while a dentist imaged sites of interest. Multi images of the interesting area were captured using the handheld IOS from different angles of approximal and occlusal views in two steps each time using one of the illumination sources (white and blue). Figure 4 illustrates the full system architecture.

![Full system architecture](image)

As mentioned previously, Xiaoming Fu discussed using photogrammetry software to 3D reconstruct models on an orthodontic plaster cast [11]. In this study, the system software was designed to reconstruct the tooth crown. The tooth crown reconstruction algorithm is based on getting point cloud from the captured images then generate poly mesh on these points. The process requires a couple of programs: VisualSFM with CMVS/PMVS and MeshLab. Figure 5 shows the total pipeline utilized to build the 3D model.
Figure 5. Flowchart of the system design

The images are uploaded as VisualSFM input to estimate the structure from motion (SFM). As indicated, VisualSFM outputs are (.txt) and (.PLY) files which are the matrices of camera and a 3D sparse point cloud, respectively. The algorithm of Multiple Dense View Stereo (MVDS) utilizes images and the camera matrices to produce the dense 3D points cloud. The final mesh model with multi-formats is generated using the captured images and the dense points.

VisualSFM is a Graphics Processing Unit (GUI) which is implemented to produce 3D reconstructions for objects by means of SFM. The system uses many algorithms such as an incremental SFM system, Scale Invariant Feature Transform (SIFT) and the Multicore Bundle Adjustment, which is used for bundle adjustment and detecting matching features. Addendum of sparse reconstruction is used as well. This process offers to run the algorithm of Yasutaka Furukawa's PMVS/CMVS which is utilized in dense reconstruction [16].

CMVS; refers to Clustering Views of Multi-View Stereo (MVS), which is a development of Multi-View Stereo (MVS) software. MVS is a software which uses a collection of photos and their matrices parameters as an input to generate the 3D object structure in dense points cloud form. MVS algorithms are not scaled well with massive numbers of input images due to the lack of computational and memory resources. CMVS is used to analysis the photos within small sized image clusters. This lets the MVS treat each cluster autonomously and in parallel, to ensure the reconstructions unity of all the clusters would not lose any data which can be otherwise acquired from all the image groups [17].

PMVS; refers to Patch-based Multi-View Stereo. It is also a development of MVS and is included in the CMVS package. It is a software which uses a collection of photos and their camera parameters to produce 3D structure of a photographed object. It is used to reconstruct a rigid structure only and automatically deny non-rigid objects. The output is an organized series of a point’s model, which calculates both the 3D coordinates and the surface normal at each oriented point. CMVS/PMVS are used in conjugation with the VisualSFM software (Bundler) [18]. Figure 6 shows the VisualSFM/PCMVS program flow chat.

Figure 6. VisualSFM / PCMVS flow chart
MeshLab is an open source program used to process and edit the 3D triangular meshes. It submits a group of tools for 3D mesh processing and models preparation for 3D printing. These tools such as edit, clean, heal, inspect, render, texture and convert meshes [19].

The tooth reconstruction algorithm that include the 3D dense reconstruction program and final mesh model described in follows as shown in figure 7.

![](flowchart.png)

**Figure 7.** Flow chart for tooth reconstruction algorithm

### 3. Results

This section presents the experimental results that measures the effectiveness of the submitted method using a group of images. This work runs on computer laptop with the following specifications (CPU: 2.2 GHz, core i5, 8GB RAM, Windows10 64bit). In this method, real images of human teeth were scanned through handled IOS so as to reconstruct 3D teeth model as illustrated in Figure 8.

![](teeth_scanned.png)

**Figure 8.** The teeth scanned to reconstruct 3D module

In order to do the reconstruction process, multi images of the molars are captured using the handheld system from different angles at two steps, each time using one of the illumination sources (white and blue). Figure 9 shows some of the images captured.
Then, the reconstruction process done following these steps:

i. Load the images to the VisualSFM software.

ii. Employ SIFT algorithm to detect object feature points in the multiple images. Figure 10 displays the results of estimated features detection from the captured images for white LED and blue laser light. As shown, blue illumination extracts more points than white illumination for the same images. In this work, images with similar size of (1600*1200) pixels was used. Also, uncelebrated camera was used, thus VisualSFM was used to eliciting EXIF file data and focal length of all images. Focal lengths are evaluated per camera set with formula (1) which corresponds to a medium viewing angle.

\[
\text{Focal length} = 1.2 \times \text{max}(\text{width, height})
\]  

(1)

iii. Perform matching. After detecting the SIFT features in every image, VisualSFM starts to match the feature points against each other to find the object points which are visible in multiple pictures. Figures 11a and 11b show the number of matches for a couple images.
As shown in Figure 11, matching matrix of blue illumination images was superior on white illumination images. Where the white color denotes loss of matches or little created matches, while, dark red color denotes a high number of matching feature points whereas yellow and green mean a lesser number of matching feature points. Figures 12a and 12b show the enlargement of part of Figures 11a and 11b.

Sparse reconstruction, in this step the dimensions and points cloud was calculated. Once the features matching is accomplished, this process runs the bundler software and generates a sparse point cloud. The automated election of good image pairs starts the 3D reconstruction process. Thus, camera matrices are computed from the main matrix, and the 3D points are estimated utilizing triangulation method of matched points. As a result, an initial 3D point cloud of (1126) 3D points was obtained with white LED light and (8490) 3D points with blue light. The remaining images will be added sequentially. The additional images matrices are set and the produced 3D points are combined to the premier point cloud. Figures 13a and 13b show the achieved results for the 3D point cloud with the primary cameras locations.
As observed, blue illumination generates more number of 3D points of the object than white illumination. VisualSFM output was saved as (bundle.rd.out) file that holds the 3D sparse of extension (. PLY), and the camera’s matrices (.txt).

Dense reconstruction using Yasutaka Furukawa’s CMVS/PMVS was used to produce the output of dense point cloud. CMVS used the point cloud created in VisualSFM and applies MVS algorithm. CMVS use the images, cameras parameters (.txt) and the sparse 3D point cloud (. PLY) to estimate the depth of the scene using stereo view. Finally, denser point cloud was formed using the existing points cloud and the depth map of the scene. Figures 14a and 14b display the CMVS output displayed through VisualSFM. As observed, blue illumination images generate denser point cloud than white illumination.

3D mesh model was generated using MeshLab. Poisson’s surface reconstruction filter was utilized to generate the 3D mesh from the VisualSFM point cloud. Figures 15a and 15b illustrate the mesh created with Poisson’s filter and the acquired 3D model.
Close Holes filter was applied to verify the digital 3D models shown in Figure 16. To get a full 3D view of teeth by closing the holes and spaces which produce from the absence of feature points in the places where the view is obstructed by other teeth in the mouth. Then the model scale was converted from an arbitrary to a real-world scale using MeshLab formula (2).

$$\text{Scale Factor} = \frac{\text{measure reference}}{\text{mesh measure}}$$

Figure 16. Final 3D module generation with (a) white LED light, (b) blue light

Finally, the CAD model was printed using 3D printer as shown in Figure 17.

Figure 17. Final 3D printed model

Table 1. Dimensions for real and model of the teeth

| Tooth parameter | Dimension from tooth (cm) | Dimension from real tooth (cm) | Accumulated Error (cm) |
|-----------------|---------------------------|-------------------------------|------------------------|
| Tooth surface length (Mesiodistal Diameter of crown) | 1.023 | 1 | 0.003 |
| Tooth surface width | 0.711 | 0.7 | 0.011 |
| Apical occlusal length of tooth crown/crown height | 0.699 | 0.6 | 0.131 |

The measurement errors varied in a wide range from 0.003 cm to 0.131 cm. The results indicate that the errors in the Mesiodistal diameter of the crown of individual model were slightly higher than that in the real teeth. This was due to the shape of the teeth surface at which the view is obstructed by other teeth in the mouth, which makes the automated reconstruction software to consider additional points from the adjacent teeth which consider as noise points. Margin points and noises were removed when processing and calculating measurements using Mesh Lab, leading to control of these errors. Also, this problem can be avoided by using higher resolution images.
Measurement errors in the cervical occlusal length of the crown were slightly lower than that in the real teeth. This was due to the gingivitis among the teeth that causing missing and unmatching points in the images captured from the side. These were fixed when processing and calculating measurements using Mesh Lab, leading to control of these errors. Also, this problem can be avoided by using higher resolution images.

The comparison of the outcome of this study with other literature reviews [9, 10, 11] implies that the recommended system is reliable that shows good accuracy of teeth crown details and measurements, but that there are nevertheless some sections which can influence the accuracy of the reconstruction. These sections related to the difficulty of images capturing and the efficiency and resolution of the used camera. As well as errors resulting from subject angulation errors in 3D and the physical hand and arm trembling.

4. Conclusion

3D reconstruction occupies an important method to create objects in a photorealistic way essentially in biomedical application. For 3D teeth scanner applications, the precision in teeth details and dimensions and facilitated use are the fundamental points that must be considered [20]. This work presents an experimental method to design low-cost movable system used for 3D scanning of the teeth. The proposed system is based on utilizing photogrammetric open source software packages (VisualSFM, CMVS/PMVS, and MeshLab) with two sources of illumination (405 nm blue laser and white LED) for 3D teeth reconstruction in order to get high accuracy 3D model with details and measurements close to reality.

From the reconstruction results, the following can be observed:

1. The VisualSFM features process reconstruction runs better within texture surfaces. This makes VisualSFM less efficient if insufficient features are revealed such as white and unified color objects. Thus using the appropriate blue illumination gives additional features to the teeth surface that enhance the performance of VisualSFM and give better results than white illumination due to the fact that teeth are white and poor textured.

2. By using sequence video images, the 3D reconstruction measuring casual error was avoided since it raises with increasing distance between captured images of the scanned object.

3. By using the low power laser instead of the LEDs light it will save the power and heating produce from the many numbers of the LEDs, in present work, the 405 nm low power laser diode was used with its minimum power, while six LEDs visible light were used to obtain the appropriate illumination.

The results demonstrate elevated precision of teeth details which are concerned with reconstruction algorithm and software which produce good 3D mesh of human teeth.

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