Long Term Three Dimensional Tracking of Orthodontic Patients Using Registered Cone Beam CT and Photogrammetry

Pierre Boulanger[1], Carlos Flores-Mir[1], Juan F. Ramirez[2], Elizabeth Mesa[2], and John W. Branch[2]

[1]University of Alberta, Edmonton, Alberta and [2]National University of Colombia, Medellin, Colombia

Abstract— ***The measurements from registered images obtained from Cone Beam Computed Tomography (CBCT) and a photogrammetric sensor are used to track three-dimensional shape variations of orthodontic patients before and after their treatments. The methodology consists of five main steps: (1) the patient's bone and skin shapes are measured in 3D using the fusion of images from a CBCT and a photogrammetric sensor. (2) The bone shape is extracted from the CBCT data using a standard marching cube algorithm. (3) The bone and skin shape measurements are registered using titanium targets located on the head of the patient. (4) Using a manual segmentation technique the head and lower jaw geometry are extracted separately to deal with jaw motion at the different record visits. (5) Using natural features of the upper head the two datasets are then registered with each other and then compared to evaluate bone, teeth, and skin displacements before and after treatments. This procedure is now used at the University of Alberta orthodontic clinic.***

Introduction

In the past two decades 3-D medical imaging has gone a long way from standard Computed Tomography (CT) with x-ray doses that were far too high to justify its regular for normal orthodontic situations. It has been shown by Roberts et al. [1] that new Cone Beam CT (CBCT) doses are in general an order of magnitude or more lower than conventional CT making it safer for normal orthodontic situations. As discussed Roberts [1], CBCT x-ray doses are still significantly higher than those from conventional dental radiography making it imperative that their use be fully justified over conventional techniques before they are carried out. By combining CBCT for 3D bone shape measurements with photogrammetric sensors for skin shape measurements (see Figure 1), we will demonstrate that it is now possible to completely track orthodontic patients shape variations along their treatments, looking for soft tissue as well as bone and teeth displacements. This is a quantum leap from normal 2D practice as described in [2]. Cavalcanti *et al* [3] demonstrated that some of the commonly used landmarks were more readily identified in 3-D reconstructions of CT images. Three-dimensional Computed Tomography provides precise information according to numerous studies described in [6]. Hildebolt and Vannier [7] concluded that the measurements techniques in 3D-CT were far superior to those in which measurements were obtained directly from the original CT slices. Cavalcanti *et al* [6] also reported that measurement of anatomical landmarks by 3-D CT is accurate enough for surgical planning and treatment evaluation of craniofacial fractures.

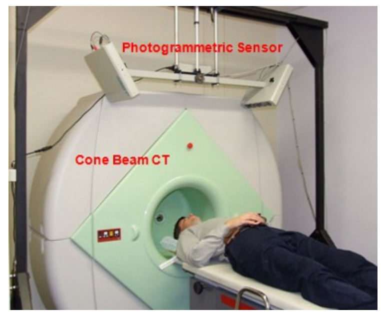


Figure 1: Fusion of CBCT and photogrammetric sensor

Once 3-D geometry is obtained from a CBCT, this information has multiple applications in the craniofacial area as described in [4]. It has been used in pre-operative planning, surgery simulation, postoperative evaluation, cephalometric, evaluation of deformities, etc. Uechi et al [5] presented a method for simulating orthognathic surgery by using a multi-modal image-fusion technique. The advantage of this simulation is to familiarize the surgeon with the operational procedures of a particular patient and to provide a way to formulate the most suitable surgical blueprint. Using CT data, Lee et al [8] evaluated large cranial defects to produce implants for reconstruction and estimation of the final results.

The aim of this paper is to describe a methodology to track orthodontic patients shape changes along their treatments. This implies that one needs to be able, not only to register CBCT sensor data for bone shape with a photogrammetric sensor for skin shape at each visit, but also to be able to compare their dimensional change between visits. The implemented methodology consists of six main steps:

1. At each visit (before starting treatment and once it is completed), the patient bone and skin 3D shape measurements are obtained using the fusion of CBCT and a photogrammetric sensor;
2. The bone geometry is extracted from the CBCT data using a standard marching cube algorithm [9][10];
3. At each visit, the bone and skin 3D measurements are registered using titanium targets;
4. Using a manual segmentation technique, the upper-head and the lower jaw are extracted separately.
5. The upper-head is then registered and compared at various times using natural landmarks for initial

registration and robust global registration to get the final transformation;

6. The lower jaws are then registered independently using the same method.

In Section II, we will describe what features are important to track in orthodontic patients. In Section III, we will discuss the various sensors used in this system. In Section IV, we will describe how to register the photogrammetric sensor with the geometry extracted from the CBCT data. In Section V, we will describe how to register and compare the two datasets between visits, and we will conclude discussing the advantages of the current methodology.

II -Tracking Orthodontic Patients Dimensional Changes

As described in [11], three-dimensional imaging provides the true anatomical data necessary to expand clinical practices and researches into evidence-based practices along with the necessary clinical experience of the practitioner. The need to track patient dimensional changes in orthodontic procedures is critical to understand the evolution of the patient over time in order to plan procedures, or to determine whether or not corrective measures are necessary during the treatments. In orthodontic treatments many geometric parameters need to be tracked. Those range from surface changes like profile improvements to teeth displacements or skeletal modifications. One of the problems with orthodontic dimensional shape tracking is that some of the treatments are very long and require being able to compare dimensional changes without reference targets. One can see at Figure 2 a patient changes after a one-year treatment.

(a) (b)

Figure 2: (a) Photographic record of a patient before treatment, and (b) one year after treatment.

II-Shape Acquisition System

As illustrated at Figure 1, the shape acquisition system is composed of a NewTom model QR - DVT 9000 volumetric tomography machine based on Cone Beam technology and a 3DMD photogrammetric digitizing station. The NewTom technology allows to obtain, through only one complete rotation of the X-ray generator and detector around the patient head, all the necessary data for the volumetric reconstruction which reduces significantly x-ray dosages to the patient. The scan time is about 75 seconds but through a pulsating x-ray source which reduces the actual radiation time to about twelve seconds. At the end of the scan, a quick reconstruction of an axial section of the patient head allows the operator to assess whether the data is correct, then the patient is digitized by the photogrammetric system. The raw data of the scan is processed to reconstruct the chosen volume in an area selected by the operator. The primary reconstruction gives images with a sampling step chosen by the operator (0.2 to 0.5 mm).

Once the patient is retracted from the NewTom machine the skin shape, 3D data and color are digitized using a photogrammetric 3DMD digitizing station mounted on top of the NewTom as illustrated at Figure 1. The 3DMD studio is based on digital stereo photogrammetry which is a method of obtaining 3D measurements by correlating two or more stereo pairs of photographs taken simultaneously by high-speed video cameras. One great advantage of the 3DMD system is that the images needed to reconstruct a model are taken in a very short period of time (in less than 1/500th of a second) and then processed using their own image analysis software. The 3DMD system projects a random pattern onto the skin surface where a sophisticated image processing software identifies and matches those patterns between the four synchronized images and generates a composite 3D model by triangulating the points. Once the 3D geometry model has been produced, the software maps the color texture information onto the model using other high-resolution color cameras. The resulting model is a triangulated set of XYZ data points with an associated texture coordinate that relates each vertex to two color images, one for the left and one for the right.

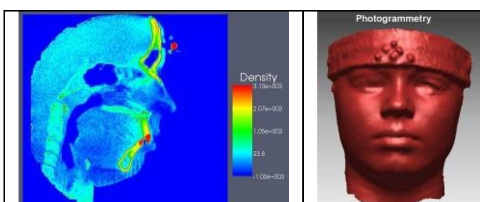
IV-Fusion of CBCT and Photogrammetry Data Using Titanium Targets

In order to be able to fuse CBCT data with photogrammetric sensor data it is key to make sure both sensors are calibrated properly. In both cases calibration targets are provided that allow computing calibration parameters by minimizing estimated target positions with exact positions in 3D space. After calibration, it is necessary to create a reference structure for registering CBCT data with photogrammetric data. To be practical, these markers had to be easy to reconstruct and identify. In our registration procedure six titanium spheres of 9 mm diameter were located on the forehead of the patient (see Figure 3). One advantage of titanium is that it does not scatter x-ray and it is also non-magnetic. This is important as one would like to eventually be able to use the same procedure to register the dataset with MRI data. One can see at Figure 4a the titanium targets as viewed by the CBCT scanner and at Figure 4b the same targets as viewed by the photogrammetric sensor.

The next step is to register the information from both systems. One of the first steps is to convert the CT data saved in Digital Imaging and Communications in medicine (DICOM) format into geometry that can then be used to find the rigid transformation between CBCT data and the photogrammetric data. In order to do so, one can import the DICOM data into Paraview (www.Paraview.org) an OpenSource volumetric data processing and visualization software. One of the great advantages of Paraview is its excellent implementation of the marching cube algorithm [10], which is able to convert at high precision CBCT data into usable geometry. Using this software, the information was segmented into contours that correspond to different densities (see Figure 5); the selected contours in the process corresponded to densities of skin and bone.

The segmented data were then saved as polygonal data and then imported in a commercial polygon processing software called RapidForm. Using this software, the noise and holes generated by the scanning process were fixed; however, in order to keep the original scanning accuracy the same, the modifications were limited to point elimination operations. The processing results are shown at Figure 4(b) and Figure 5.

Figure 3. Titanium markers.



(a)	(b)

Figure 4: Titanium targets viewed by the CBCT scanner and by the photogrammetric sensor.

Following data filtering, the next step is to register the photogrammetric data with the CBCT data. The first step is to approximate the scanned titanium targets in both modalities by fitting perfect geometrical spheres of known diameter. The spheres were fitted using a tool provided in RapidForm. The main results are sphere locations in 3D space and approximation error estimates. For the CBCT data, the max fitting error was 1.2 mm and for the photogrammetric data 0.8 mm.

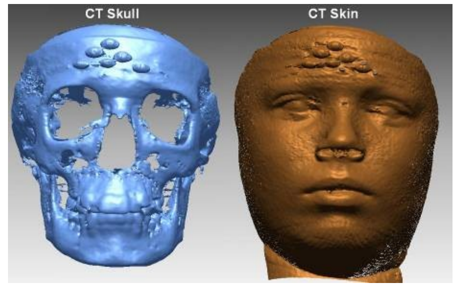


Figure 5: Results of CBCT segmentation process using the marching cube algorithm.

One advantage of using known shapes like spheres is that one can estimate the true accuracy of the sensors as those spheres are machined at micron precision. Following the sphere centers estimation, one can then compute the rigid transformation between spheres and compute a global transformation matrix between them that can then be applied to the entire dataset. The result of this registration process is illustrated at Figure 6.

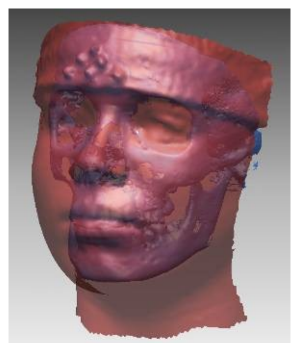


Figure 6: Results for registration between CBCT skull and photogrammetric geometry.

V-Registration Between Visits

To register information between visits, it was obviously not possible to use the markers, since there was no way to ensure markers could be located at the same place. Hence the only ways to register between visits were to use common areas or natural landmarks. In both cases (areas and landmarks), the elements to consider were that the features had to be easily identifiable and did not change between visits. The registration process is the following:

1. Register the current visit dataset (CBCT and photogrammetric) using the previous method;
2. Hand select the lower jaw triangles and separate them from the upper part of the head into two groups;
3. Select the two upper head triangle groups at time T_1 and T_2;
4. Locate common points in both groups;
5. Register the points using RapidForm initial registration tool;

6. Register both upper head triangle groups with the global registration tool setting the miss registration threshold to max 1.5 mm.
7. Compare both datasets using the difference tool;
8. Take both lower jaw triangle groups and register them the same way;
9. Compare both lower jaws using the comparison tool.

One can see at Figure 7, the registration of the two skulls using upper head registration technique. One can see that for the upper-head region the errors between the two skulls are in bound of the CBCT sensor precision. At Figure 7, one can see clearly the canine displacement changes that occurred in the upper jaw during the year and show the robustness of the registration algorithm to outliers. If we only rely on this registration procedure one could think that the lower jaw had a major dimensional change that occurred over the year when in fact there were no major changes in the lower jaw due to orthodontic changes. This apparent change is due to the fact that the lower jaw is independent from the upper head and that at the second visit it was not at the same position. To prove that there was no real-change in the lower jaw, we performed the same registration process but this time with the lower jaw triangle group. As one can see at Figure 8 there are no significant differences between the two visits as most of the data variations are in bound of the CBCT precision of 1.5 mm.

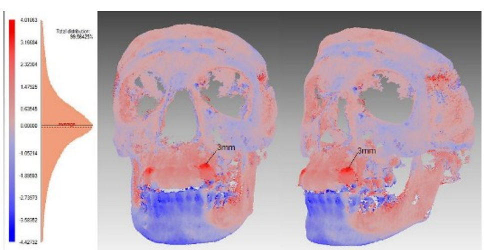


Figure 7: Deviation between time T_1 and T_2 using upper-head global registration

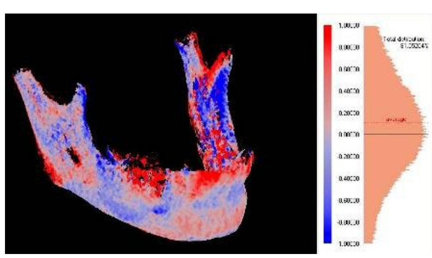


Figure 8: Deviation between lower jaw from T_1 and jaw from T_2.

Conclusion

The ability to integrate multiple modalities like CBCT and photogrammetric sensors could be key to an evidence-based practice as described by the ADA as 3D data has been shown to be more accurate than conventional 2D imaging. We have demonstrated in this paper that one can register photogrammetric and CBCT data using titanium spherical markers. The final registration precision was found to be 1.1 mm, which is in bound with the CBCT precision specification provided, by NewTom. In addition to be able to fuse those modalities, we were also able to register the dataset between visits by using a global robust registration of the upper head. This robustness to outliers was illustrated by the fact that the global registration was not affected by a 3 mm change of the upper canine caused by the orthodontic procedure. This is due to the fact that the algorithm used by RapidForm eliminates any outlier from the final global registration based on a specified threshold that was set at 1.5 mm corresponding to the approximate precision of the CBCT data. Our next experiment will be to deform the photogrammetric data between visits based on the upper and lower jaw registration. We are currently adapting thick shell finite element code with large displacement that was designed for industrial inspection of deformable part to this problem. We are also looking into color calibration procedure that will allow us to monitor not only geometric changes but also colorimetric changes. Currently a significant number of orthodontic patients at the University of Alberta orthodontic clinic are monitored by these systems.

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