Multi-modal Imaging for Shape Modelling of Dental Anatomies

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Abstract. In dentistry, standard radiographic imaging is a minimally invasive approach for anatomic tissue visualization and diagnostic assessment. However, this method does not provide 3D geometries of complete dental shapes, including crowns and roots, which are usually obtained by Computerized Tomography (CT) techniques. This paper describes a shape modelling process based on multi-modal imaging methodologies. In particular, 2D panoramic radiographs and 3D digital plaster casts, obtained by an optical scanner, are used to guide the creation of both shapes and orientations of complete teeth through the geometrical manipulation of general dental templates. The proposed methodology is independent on the tomographic device used to collect the panoramic radiograph.

Keywords: Multi-modal imaging · Dental shape modelling · PAN radiograph · Discrete Radon Transform

1 Introduction

Orthodontics is the branch of dentistry concerned with the study and treatment of irregular bites and deals with the practice of manipulating patient dentition in order to provide better functionalities and appearances.

Detection and correction of malocclusion problems caused by teeth irregularities and/or disproportionate jaw relationships represent the most critical aspects within an orthodontic diagnosis and treatment planning. The most common methodologies for non-surgical orthodontic treatments are based on the use of fixed appliances (dental brackets) or removable appliances (clear aligners) [1]. In clinical practice, the conventional approach to orthodontic diagnoses and treatment planning processes relies on the use of plaster models, which are manually analyzed and modified by clinicians in order to simulate and plan corrective interventions. These procedures however require labor intensive and time-consuming efforts, which are mainly restricted to highly experienced technicians. Recent progresses in three-dimensional surface scanning devices as well as CAD (Computer Aided Design)/CAM (Computer Aided Manufacturing) technologies have made feasible the complete planning process within virtual environments and its accurate transfer to the clinical field. In particular, orthodontic alignment procedures greatly benefit from the combined use of CAD/CAM methodologies which are used to

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produce custom tight-fitting devices worn by the patients [2]. In this context, the accurate and automatic reconstruction of individual tooth shapes obtained from digital 3D dental models is the key issue for planning customized treatment processes. Optical scanners may be used to digitize plaster models thus providing geometric representations of tooth crowns. However, even if both clear aligners and brackets accomplish the treatment plan only by acting onto the tooth crown surfaces, a correct orthodontic treatment should also take into account tooth roots in terms of position, shape and volume. In particular, position and volume of dental roots may cause dehiscence, gingival recession as well as root and bone resorption when teeth undergo movements during therapy. Cone beam computed tomography (CBCT) could provide comprehensive 3D tooth geometries. However, concerns about radiation doses absorbed by patients are raised. For this reason, the use of computed tomography as a routine in orthodontic dentistry is still a matter of discussion. Even if CBCT has greatly reduced the dose of absorbed *x*-rays, compared to traditional computed tomography (CT), it still produces a greater *x*-ray dose than a panoramic radiograph (PAN).

2-D panoramic radiographs are a routine approach in the field of dentistry since they represent an important source of information. In particular, they are able to inexpensively record the entire maxillomandibular region on a single image with low radiation exposure for the patient. However, they are also characterized by several limitations such as: lack of any 3D information, magnification factors which strongly vary within the image thus causing distortions, patient positioning which is very critical with regard to both sharpness and distortions. As a result, not only 3D measurements are impaired, but also reliable 2D dimensions cannot be retrieved.

The present paper is aimed at investigating the possibility to recover 3D geometry of individual teeth by customizing general templates over patient-specific dental anatomy. Information about patient anatomy is obtained by integrating the optical acquisition of plaster casts with 2D panoramic radiographs. Even if the reconstruction of patient-specific 3D dental information from 2D radiographs and casts represents a challenging issue, very few attempts have been made up to now within the scientific community [3, 4]. Moreover, these studies greatly rely on the knowledge of the specific tomographic device used to acquire the PAN image. The present study is focused on the formulation of a general solution, which could infer tooth roots shape without any assumption on the specific hardware as well as parameters used to collect patient data anatomy.

2 Materials and Methods

In this paper, complete 3D dental shapes are reconstructed by integrating template models with 3D crowns data deriving from the optical acquisition of plaster casts and 2D data deriving from PAN radiographic images.

An optical scanner based on a structured light stereo vision approach has been used to reconstruct both template dental models and patient's dental casts.

Panoramic radiographs have been captured by using a Planmeca ProMax unit (Planmeca Oy, Helsinki Finland); whose data are stored and processed in DICOM format.

2.1 3D Data Acquisition System

The optical scanner (Fig. 1) is composed of a monochrome digital CCD camera (1280 × 960 pixels) and a multimedia white light DLP projector (1024 × 768 pixels) which are used as active devices for a stereo triangulation process. In this paper, a multi-temporal *Gray Code Phase Shift Profilometry* (GCPSP) method is used for the 3D shape recovery through the projection of a sequence of black and white vertical fringes whose period is progressively halved [5]. The methodology is able to provide $n_p = l_h \times l_v$ measured points (where l_h is the horizontal resolution of the projector while l_v is the vertical resolution of the camera) with a spatial resolution of 0.1 mm and an overall accuracy of 0.01 mm.

Fig. 1. Optical scanner during the acquisition process of a tooth template.

The optical devices are integrated with two mechanical turntables (Fig. 1) which allow the automatic merging of different measurements collected from various directions conveniently selected.

2.2 Input Data

The methodology requires three different input data: (1) general dental CAD templates, (2) dental crowns shape and (3) a PAN image. Crowns shape and PAN image are patient-specific data while teeth templates can be obtained from existing libraries.

Dental CAD Templates. Teeth template models are composed of complete teeth crowns and roots and are placed in adequately shaped holes within transparent plastic soft tissue reproduction (Fig. 2). Teeth can be easily removed from their housing in order to allow full reconstructions through the 3D scanner without optical occlusions.

Fig. 2. Example of superior and inferior dental arch templates.

Patient Crowns Reconstruction. The patient dental crowns geometry can be acquired by scanning the plaster cast. Figure 3a shows the final digital reproduction of the patient tooth crowns with surrounding gingival tissue (digital mouth model) as obtained by merging twelve acquisitions of the superior plaster cast captured by different views. Tooth crown regions are segmented and disconnected from the oral soft tissue by exploiting the curvature of the digital mouth model. This model contains ridges and margin lines, which highlight the boundaries between different teeth, and between teeth and soft tissue. Regions with abrupt shape variations can be outlined by using curvature information [5]. Segmented crown shapes are finally closed by using computer-based filling tools (Fig. 3b).

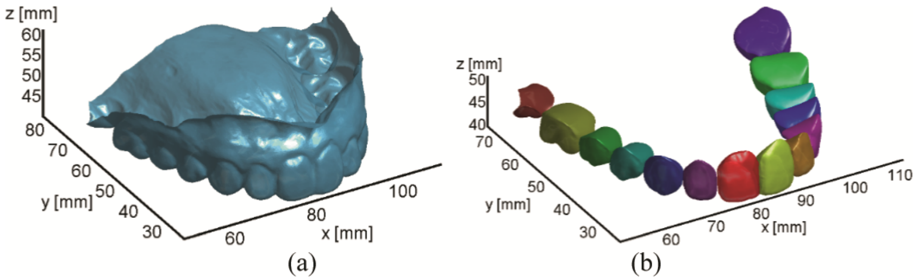

Fig. 3. (a) Reconstruction of the superior plaster cast as obtained by the optical scanner and (b) segmented patient crowns geometries.

Panoramic Radiograph. Dental panoramic systems provide comprehensive and detailed views of the patient maxillo-mandibular region by reproducing both dental arches on a single image film (Fig. 4).

A panoramic radiograph is acquired by simultaneously rotating the *x*-ray tube and the film around a single point or axis (*rotation center*). This process, which is known as tomography, allows the sharp imaging of the body regions disposed within a 3D horseshoe shaped volume (*focal trough* or *image layer*) while blurring superimposed structures from other layers. The rotation center changes as the film and *x*-ray tube are rotated around the patient's head. Location and number of rotation centers influence both size

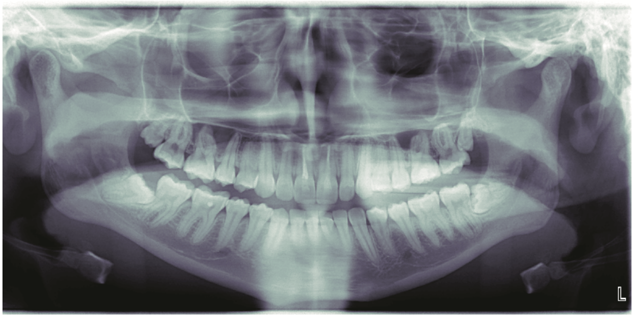

Fig. 4. Example of panoramic (PAN) radiograph.

and shape of the focal through which is therefore designed by manufacturers in order to accommodate the average jaw.

2.3 Methodology

The proposed methodology is based on scaling the tooth CAD template models accordingly to the information included within the patient segmented tooth crowns shape and the PAN image.

Segmented crown models are used to determine the axis of each patient tooth. Teeth templates are then linearly scaled by using non-uniform scale factors along three different dimensions (Fig. 5). In particular, the tooth width (taken along the mesiodistal line) and the tooth depth (taken along the vestibulo-lingual direction) values are directly determined from the patient crown geometries. The tooth height (taken along the vertical direction of the panoramic radiograph) is rather estimated by using the PAN image.

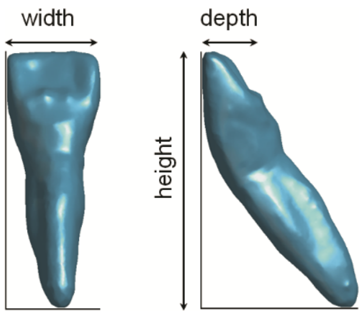

Fig. 5. Tooth dimensions used to scale CAD templates.

The height estimation process, which represents the core of the proposed method, is based on the reconstruction of a synthetic PAN image from the 3D patient crowns geometries. A panoramic radiograph essentially represents the sum of x-ray attenuation along each ray transmitted from the source to the film [6]. The attenuation is due to the x-ray absorption by tissues along the ray. For this reason, it is possible to emulate a panoramic radiograph by taking 2D projections through a data volume. In this paper, the *Discrete Radon Transform* (DRT) is used to calculate finite pixel intensity sums along rays normal to a curve, which approximate the medial axis of the crowns arch.

The whole methodology can be summarized in the following steps:

- Uniform scaling of the complete dental template arch by using the patient digitized cast (Fig. 6a);
- Alignment of each tooth template on the corresponding patient tooth crown geometry in order to determine the orientation and position with respect to the bone structure;
- Non-uniform scaling by using the tooth width and depth values (Fig. 6b);
- Tooth height estimation from the PAN image by simulating the panoramic radiograph process through the *Discrete Radon Transform* applied on the reconstructed patient crowns model.

The first three steps are quite straightforward and can be accomplished by using any CAD software. The last step is fully detailed in the following section.

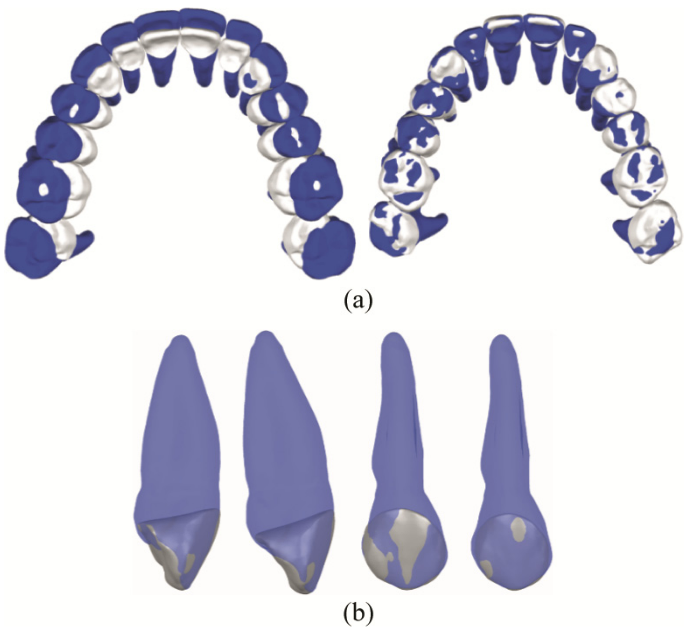

Fig. 6. (a) Uniform scaling of the complete dental template arch and (b) two examples of non-uniform tooth scaling by using width and depth values.

Tooth Height Estimation. The 3D patient crowns model must be spatially oriented, by a rigid motion, in order to make its projection consistent with the corresponding crowns region in the PAN radiograph. A set of n corresponding markers $[P^i_{PAN} \equiv (x^i_{PAN}, y^i_{PAN}, z^i_{PAN}), P^i_{cr} \equiv (x^i_{cr}, y^i_{cr}, z^i_{cr})]$ is interactively selected on crown regions of both PAN image and segmented crowns model. A rigid motion, applied to the 3D model and described by a rotation matrix (R) and a translation vector (T), is then determined by minimizing an objective function defined as:

$$f(R, T) = \sum_{i=1}^{n} \left\| \Delta z^{i}_{PAN} - \Delta z^{i}_{cr} \right\|^{2} \tag{1}$$

This transformation guarantees the alignment between the 3D patient crowns model and the radiograph along the z-direction (Fig. 7). A further transformation is then required in order to project the 3D model onto the panoramic image. This process is accomplished by computing multiple parallel-beam projections, from different angles, using the DRT. In particular, a 2D image is firstly created by projecting the crowns model onto the X_{cr}-Y_{cr} plane (Fig. 8). A fourth order polynomial curve (γ) is then determined by interpolating the projection of the selected $P^{i}_{cr} \equiv \left(x^{i}_{cr}, y^{i}_{cr}\right)$ points.

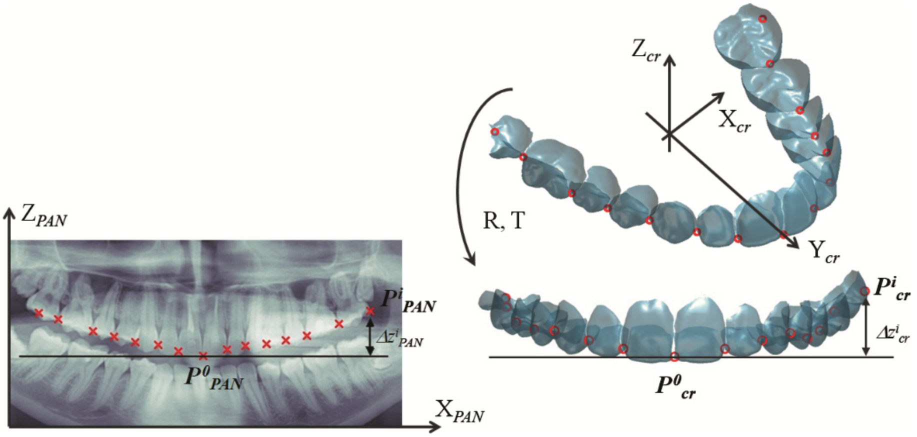

Fig. 7. Alignment between 3D crowns model and PAN image along the z-direction.

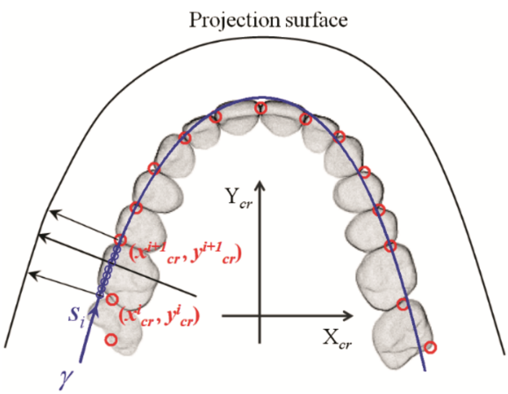

Fig. 8. Projection scheme of the 3D patient crowns model.

The 3D model is vertically sliced with the same vertical resolution of the PAN image. For each horizontal slice, crown contours are projected along the direction normal to γ in correspondence of each curve point by using the DRT (Fig. 8). The curve point sampling (s_i) is piecewisely estimated by matching the number of samples between two consecutive P^i_{cr} points with the number of pixels along the X_{PAN} direction between the corresponding P^i_{PAN} points. Figure 9a shows the DRT results for the projection of the crowns model illustrated in Fig. 3b, while Fig. 9b and c show its superimposition on the original PAN image.

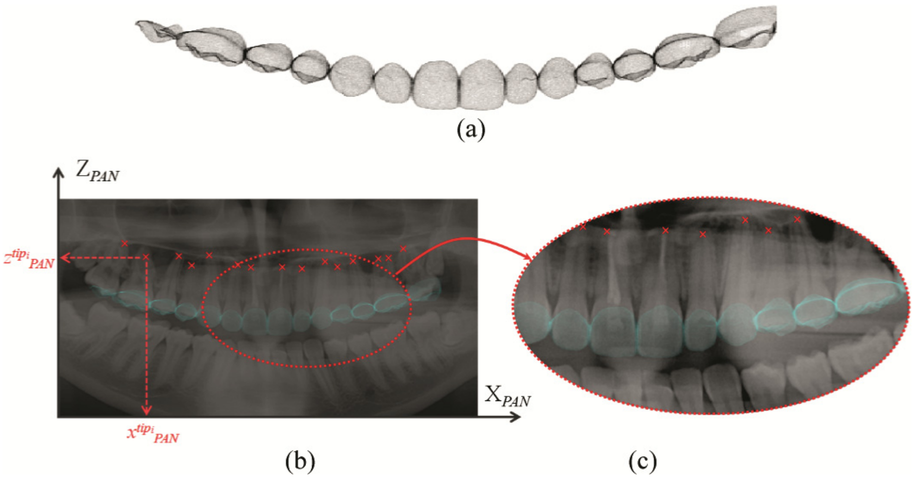

Fig. 9. (a) DRT projection of the 3D patient crowns model, (b) superimposition of the projection on the PAN image along with a detail (c). The crowns model projection is highlighted with a transparent cyan color (Color figure online).

Tooth heights are then extracted from the PAN image by the selection of root tips, which are back-projected onto the 3D model. This back-projection is performed by considering the coordinates of the root tip in the PAN image. The z-coordinate, up to a scale factor, is used to identify the slice to which the 3D root tip belongs:

$$z^{tip_i}_{cr} = scale_z \cdot z^{tip_i}_{PAN} \quad (2)$$

The x-coordinate is instead used to retrieve the curvilinear coordinate along the γ curve by:

$$s^{tip_i} = x^{tip_i}_{PAN} \quad (3)$$

The line normal to γ and passing from s^{tipi} describes the projection ray through the root tip. It is then possible the spatial identification of a direction on which the 3D root tip must certainly lie (*constraint line*). The template tooth model, already scaled by considering width and depth values can then be finally scaled along the height direction in order to approach the above outlined constraint line. Clearly, an indetermination about the root inclination remains since the tooth root could be indifferently oriented to the buccal or lingual side of dentition. However, the preventive alignment of the tooth template on the patient crown model should guarantee the correct orientation of the final reconstructed tooth.

3 Results

The feasibility of the proposed methodology has been verified by reconstructing some teeth of a female patient superior dental arch. Figure 10 shows two views of the CAD templates aligned and scaled (using tooth width and depth values) on the crowns model, along with the directions on which respective root tips should lie. CAD templates are then further scaled along the tooth heights while tooth axes are oriented in order to intersect the respective constraint lines (Fig. 11). Crown geometries, acquired by the optical scanner, and root geometries, estimated by scaling CAD templates, are then merged together in order to create the final digital tooth model (Fig. 12).

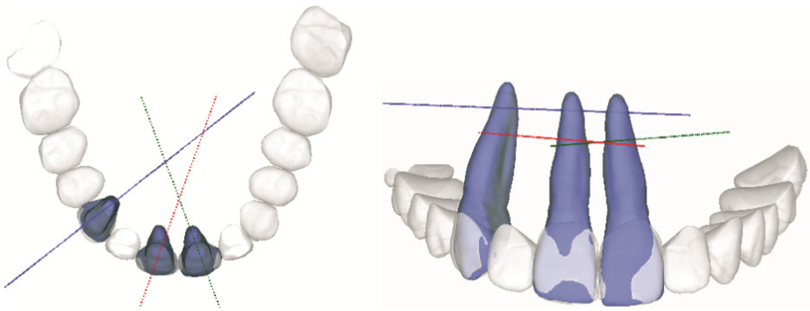

Fig. 10. CAD templates aligned and scaled on the crowns model with the respective constraint lines for root tips.

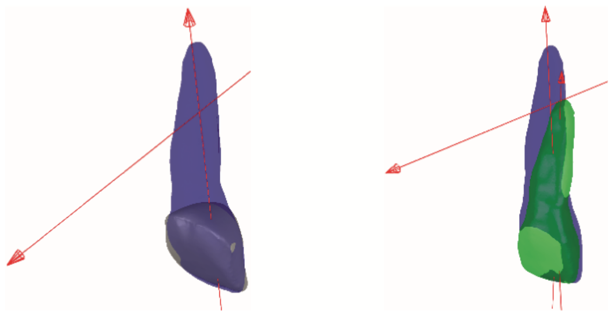

Fig. 11. Final height scaling and orientation (green model) of the tooth CAD template (blue model) (Color figure online).

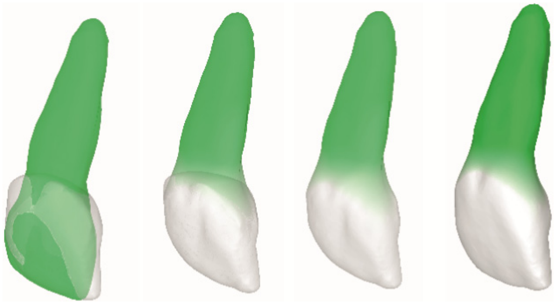

Fig. 12. Merging process between crown geometry (gray model) and scaled tooth CAD template (green model) (Color figure online).

The reconstructed tooth shapes can be compared to those obtained by processing volumetric data from patient CBCT scans. In this case, segmented tooth geometries from CBCT data (Fig. 13a) can be used as ground truth to assess the accuracy of 3D models reconstructed by using minimally invasive imaging modalities (Fig. 13b, c).

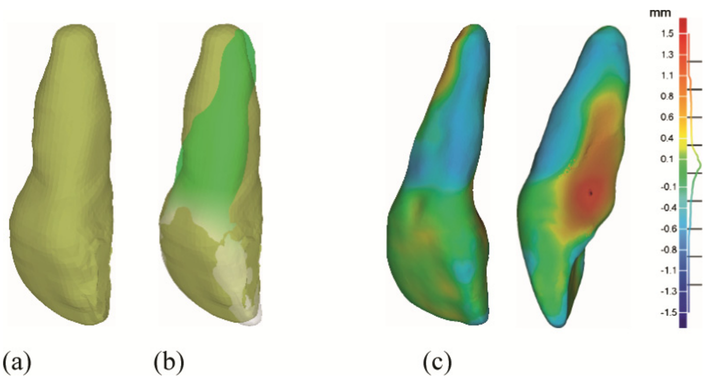

Fig. 13. (a) CBCT tooth ground truth, (b) overlapping between CBCT and reconstructed tooth model, (c) discrepancies between the two models.

4 Conclusions

In the field of orthodontic dentistry, one of the main challenges relies on the accurate determination of 3D dentition geometries by exposing the patient to the minimum radiation dose. In this context, the present paper outlines a methodology to infer 3D shape of tooth roots by combining the patient digital plaster cast with a panoramic radiograph. The method investigates the possibility to adapt general dental CAD templates over the real anatomy by exploiting geometrical information contained within the panoramic image and the digital plaster cast. The proposed modelling approach, which has showed encouraging preliminary results, allows a generalized formulation of the problem since assumptions about the tomographic device used for radiographic data capturing are not required.

Many are the variables involved in the adopted formulation. In particular, key issues are represented by the optimization of the γ curve, whose slope determines the orientation of root tip constraint lines, and the accurate evaluation of magnification factors along the z-direction of the PAN image.

These topics certainly require further research activities taking also into account, for example, additional information that could be extracted by supplementary lateral radiographs.

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