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# Geometrical modeling of complete dental shapes by using panoramic X-ray, digital mouth data and anatomical templates

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## Abstract

In the field of orthodontic planning, the creation of a complete digital dental model to simulate and predict treatments is of utmost importance. Nowadays, orthodontists use panoramic radiographs (PAN) and dental crown representations obtained by optical scanning. However, these data do not contain any 3D information regarding tooth root geometries. A reliable orthodontic treatment should instead take into account entire geometrical models of dental shapes in order to better predict tooth movements.

This paper presents a methodology to create complete 3D patient dental anatomies by combining digital mouth models and panoramic radiographs. The modeling process is based on using crown surfaces, reconstructed by optical scanning, and root geometries, obtained by adapting anatomical CAD templates over patient specific information extracted from radiographic data. The radiographic process is virtually replicated on crown digital geometries through the Discrete Radon Transform (DRT). The resulting virtual PAN image is used to integrate the actual radiographic data and the digital mouth model. This procedure provides the root references on the 3D digital crown models, which guide a shape adjustment of the dental CAD templates. The entire geometrical models are finally created by merging dental crowns, captured by optical scanning, and root geometries, obtained from the CAD templates.

**Keywords**: Dental Shape Reconstruction, Panoramic Radiograph, 3D Optical Scanning, Dental Template.

# 1 Introduction

Nowadays, Computer-Aided Design (CAD) plays a crucial role in several medical applications including customized prosthesis design, virtual treatment planning and computer-guided surgery. Generally, a CAD-based biomedical tool requires three-dimensional modeling of anatomical shapes, which are used for downstream clinical simulations [1]. The development of imaging technologies and reverse engineering methods has given a great support to the widespread use of digital human models for diagnosis and treatment planning.

For a long time, dentistry has demonstrated a great interest in using CAD tools for clinical practice, with reference to implant design, prosthetic rehabilitation and bite correction. Within dentistry, orthodontics is a clinical specialty dealing with the study and the treatment of irregular bites (malocclusions) in order to provide better functionalities and appearances. The most common methodologies for non-surgical orthodontic treatments are based on the use of fixed or removable appliances [2, 3] to correct tooth positions. In clinical practice, the conventional approach to orthodontic diagnoses and treatment planning relies on the use of plaster models of patients' mouths, which are manually analyzed and modified in order to plan corrective interventions. However, these procedures require labor intensive and time consuming efforts, which are restricted to highly experienced technicians.

Recent progresses in three-dimensional surface scanning devices have allowed the development of computer-based tools dedicated to complete planning processes. Orthodontic treatments greatly benefit from the use of CAD methodologies to produce customized tight-fitting appliances. In this context, the accurate reconstruction of individual tooth shapes obtained from digital 3D dental models represents a crucial issue for planning customized treatment processes. Optical scanners are used to digitize patients' mouths thus providing geometric representations of tooth crowns. However, 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. Different recording technologies may be used to produce medical images of internal anatomical parts, such as X-ray radiography and computed tomography. 2-D panoramic radiographs (PAN) are considered routine diagnostic supports in dentistry, though the output data are limited to bi-dimensional information. The use of cone beam computed tomography (CBCT) provides 3D tooth shapes, which include root geometries. However, the use of CBCT still represents a matter of discussion in dentistry, since the radiations are higher than those emitted by a standard radiographic process.

The present paper is aimed at modeling 3-D shapes of complete teeth by using panoramic X-ray data and digital mouth models. In particular, the proposed methodology adapts general CAD tooth templates over individual patient's anatomies by correlating optical digitalization of dental mouth models with panoramic radiographs. The radiographic capturing process is replicated onto crown geometries, obtained by segmenting the digital mouth model, through the Discrete Radon Transform (DRT). A virtual PAN image is created and used to integrate the patient's radiographic data on the digitized crown models, thus providing root references over dental anatomies. The root references guide a shape adapting of dental CAD templates. The final dental models are obtained by merging the accurate crown data, captured by the optical scanning, and the root geometries, approximated from the adapted CAD template shapes.

The effectiveness of the developed methodology has been evaluated by comparing the reconstructed tooth shapes with those obtained by processing CBCT scans, which have been used as ground truth.

## 2 Background

The computer-aided reconstruction of human dental models represents a wide research area due to the growing interest towards the virtual planning of orthodontic treatments. The different methodologies developed by the research community can be classified as follows: 1) reconstruction of crown geometries through the segmentation of dental surfaces obtained by scanning plaster casts [4-8]; 2) reconstruction of complete tooth geometries through the segmentation of tomographic data obtained by either CT or CBCT scanning [9-11]; 3) reconstruction of complete tooth geometries by fusing crown geometries obtained by surface scanning data with root models obtained by tomographic data [12-14].

The first methodology includes approaches based on range maps generated from the dentition model [7, 8] and techniques focusing on segmenting teeth directly on 3D meshes [4-6]. These methods allow accurate geometrical reconstructions limited to crown and occlusal surfaces, since optical scanners cannot measure dental root shapes, which are not represented in plaster casts.

The segmentation of volumetric data sets deriving from tomographic imaging provides the full reconstruction of dental shapes, including root geometries, to detriment of coronal surface accuracies.

Hybrid methodologies have then been developed by integrating optical imaging and computed tomography [12-14]. These methods provide high accuracies in the reconstruction of occlusal surfaces augmented with root information. The major disadvantage of these methods relies on the use of tomographic recording, which is not considered a routine approach for standard orthodontic treatments, due to radiation issues. For this reason, alternative proposals have been recently developed by using prebuilt libraries through statistical models [15] or by combining information derived from panoramic radiography with CAD templates [16, 17]. However, very few attempts have been made up to now within the scientific community and the existent studies greatly rely on the knowledge of the specific radiographic device used to acquire PAN images. The reconstruction of patient-specific 3D dental information by combining 2D radiographs and dental impressions, still represents a challenging issue.

## 3 Geometrical modeling of complete dental shapes

The present section introduces a general approach to the geometrical modeling of complete dental shapes, which infers tooth roots without any specific assumption on the parameters used to collect patient's anatomical data. Figure 1 shows the overall workflow of the developed approach.

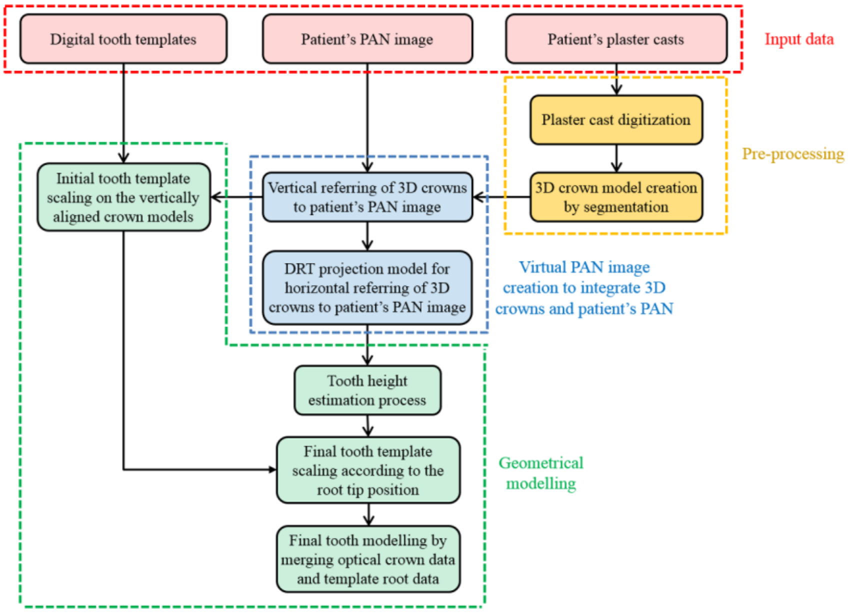


**Figure 1 -** General scheme of the proposed methodology.

### 3.1 Anatomical data acquisition

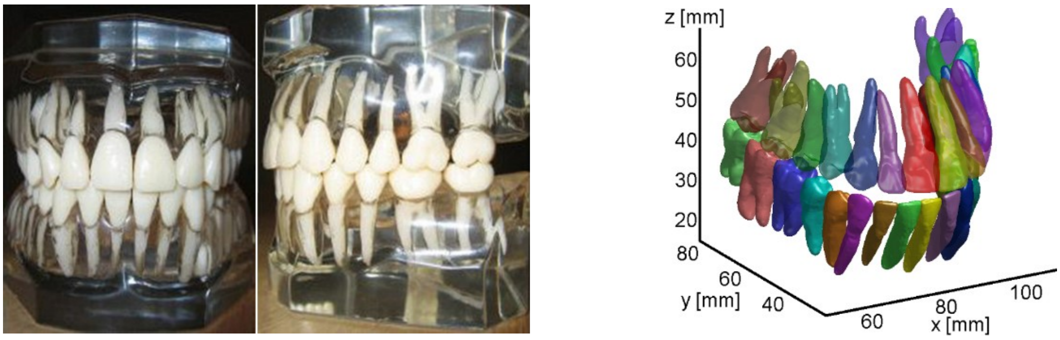
The proposed methodology uses three input data: 1) dental CAD templates, 2) dental crown shapes and 3) 2D root information.

In this paper, an optical scanner based on a structured light stereo vision approach has been used to create a library of dental templates and to reconstruct patient's dental casts. The scanner 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 [18]. 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. The methodology is able to provide surface measurements with a spatial resolution of 0.1 mm and an overall accuracy of 0.01 mm.

The optical scanning system has been used to create a library of *digital tooth templates* from reference physical models [19] of crowns and roots (Figure 2-a). Teeth are removed from their housing in order to allow full shape reconstructions through the 3D scanner (Figure 2-b).

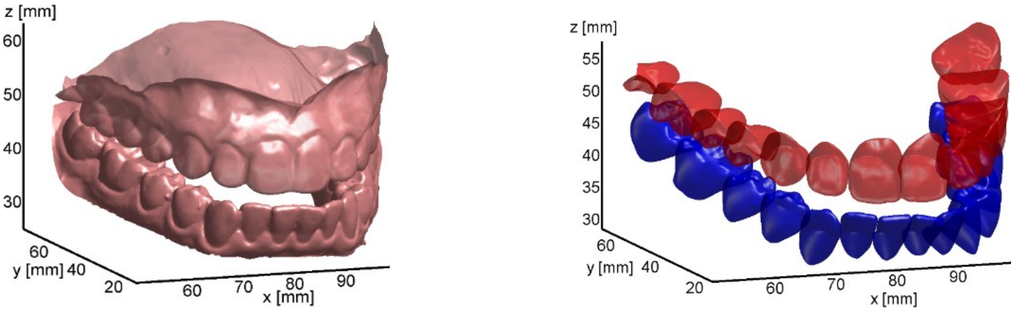
*Patient's crown shapes* are acquired by scanning plaster casts manufactured from mouth impressions. The final digital reproduction of patient's tooth crowns with surrounding gingival tissue (digital mouth model of Figure 3-a) is obtained by merging different range maps of the superior and inferior plaster casts within an automatic multi-view scanning process. A digital mouth model contains ridges and margin lines, which highlight the boundaries between adjacent teeth, and between teeth and soft tissue. Each individual crown region is segmented and disconnected from the oral soft tissue by exploiting the local curvature information [12] (Figure 3-b).

*Tooth root information* is extracted from panoramic radiographs of the patient's maxillo-mandibular regions (Figure 4). In this paper, panoramic radiographs have been captured by using a Planmeca ProMax unit (Planmeca Oy, Helsinki, Finland), whose data are stored and processed in DICOM format. A PAN image is acquired by simultaneously rotating the X-ray tube and the film around a single point or axis (rotation center). This process 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 and shape of the focal trough, which is therefore designed by manufacturers in order to accommodate the average jaw. In this work, the resolution of the PAN images is 2828 × 1376 pixels ($PAN_w \times PAN_h$). The output DICOM data also include dimensional information, which may require a correction factor to relate pixels to actual dimensions. In this paper, the correction factor has been evaluated using accurate dimensions identified in dental crown models obtained by the optical scanning.



(a) (b)

**Figure 2 -** Dental arch templates (a) and relative CAD models obtained by optical scanning (b).



(a) (b)

**Figure 3 -** Geometric reconstruction of a couple of plaster casts as obtained by the optical scanner (a) and segmented crown geometries (b).

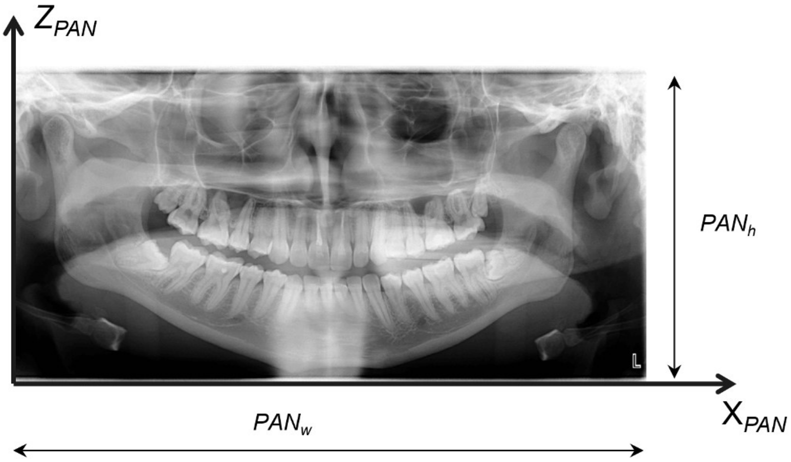


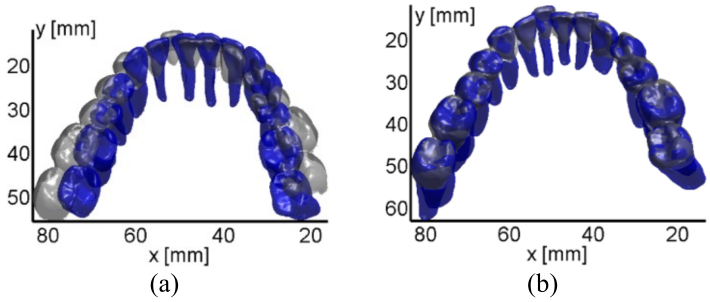
**Figure 4 -** Panoramic (PAN) radiograph.

### 3.2 Preliminary adapting of tooth templates

The methodology is based on scaling the tooth CAD template models accordingly to the information included in the segmented crown shapes and in the *actual PAN image* obtained by recording the patient's maxillo-mandibular anatomy. The whole process can be summarized in the following steps:

- preliminary uniform scaling of the entire dental template arches by using the patient's crown models (Figure 5);
- alignment of each tooth template on the corresponding tooth crown geometry in order to determine a rough position with respect to the bone structure;
- non-uniform scaling of each tooth template along priority directions;

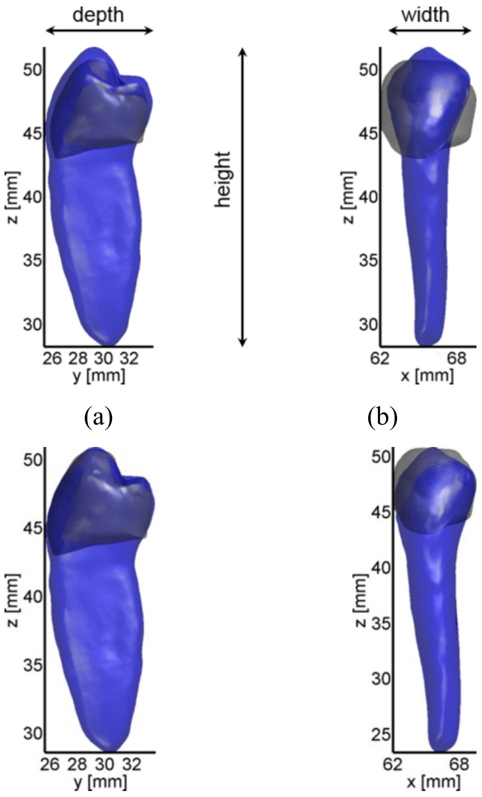
The first two steps are quite straightforward and can be accomplished by using a standard CAD software.



(a) (b)

**Figure 5 –** A complete dental template before (a) and after (b) the preliminary uniform scaling (reference crown model in grey, template shapes in blue).

The non-uniform scaling of each tooth template is carried out by a linear adapting process along three priority directions defined as illustrated in Figure 6. In particular, the *tooth width* is defined along the mesiodistal line as the maximum distance between mesial and distal surfaces of the tooth crown, while the *tooth depth* is defined along the vestibulo-lingual direction as the maximum distance between vestibular and lingual surfaces of the tooth crown. The respective scale values are directly determined from the patient's crown geometries. The *tooth height*, which is defined along the vertical direction of the panoramic radiograph, is instead estimated by exploiting the information contained within the *actual PAN image*. In particular, a *virtual PAN image* is created to correlate the patient's radiographic data to the digitized crown models, thus providing root references for height sizing.



(a) (b)

(c) (d)

**Figure 6 –** Example of non-uniform tooth scaling by using width and depth values: (a) and (b) before scaling, (c) and (d) after scaling, respectively.

### 3.3 Virtual PAN imaging to refer 3D crown models to PAN radiograph

The estimation of root shapes is based on the creation of a virtual PAN image of the 3D patient's crown geometries. A panoramic radiograph essentially represents the sum of radiation attenuation along each ray transmitted from the source to a film [20]. The attenuation is due to the X-ray absorption by human tissues along the ray. In this paper, the absorption phenomenon is emulated by taking 2D projections through 3D digital models of dental crowns on the basis of a Discrete Radon Transform (DRT). The resulting virtual PAN image provides the references to extract dimensional root data from the patient's radiograph. This procedure, which is fully detailed in the next paragraphs, is based on integrating crown models and panoramic images by the following steps: *i*) vertical referring of crown models to the PAN image, *ii*) multiple parallel-beam projections of the vertically referred crown models using the Discrete Radon Transform.

### 3.3.1 Rigid transformations for vertical referring

Generally, the dental arches captured by the optical scanner have relative spatial placements, which differ from the mouth positions assumed during the panoramic image recording. Therefore, 3D crown models (Figure 3-b) have to be reoriented by rigid motions in order to make them consistent with the corresponding crown regions in the actual PAN radiograph. The procedure is automatically extended to the preliminary aligned and scaled tooth templates, which are consequently referred to the actual PAN image.

The superior and inferior arches are vertically referred to the PAN image by introducing two sets of $m$ and $n$ corresponding markers $[P^i_{PAN} \equiv (x^i_{PAN}, y^i_{PAN}, z^i_{PAN})$, $\mathrm{P}^i_{\mathrm{cr}} \equiv (x^i_{cr}, y^i_{cr}, z^i_{cr})]$, which are interactively selected on the crown regions of both PAN image and segmented crown models (Figure 7). Two different rigid motions, described by rotation matrices ($R_s$, $R_i$) and translation vectors ($T_s$, $T_i$), are then estimated and respectively applied to the superior and inferior crown models. In particular, the transformation to be applied to the superior arch model ($R_s$, $T_s$) is determined by minimizing an objective function defined as:

$$f(R_S, T_S) = \sum_{i=1}^{m} \left\| \Delta z^i_{PAN} - \Delta z^i_{cr} \right\|^2 \tag{1}$$

where $\Delta z^i_{PAN}$ and $\Delta z^i_{cr}$ respectively represent the relative differences along the $Z_{PAN}$ and $Z_{cr}$ directions between the $i$-th point and a reference point ($P^0$). This transformation guarantees the alignment between the 3D patient superior crown model and the radiograph along the $z$-direction (Figure 7).

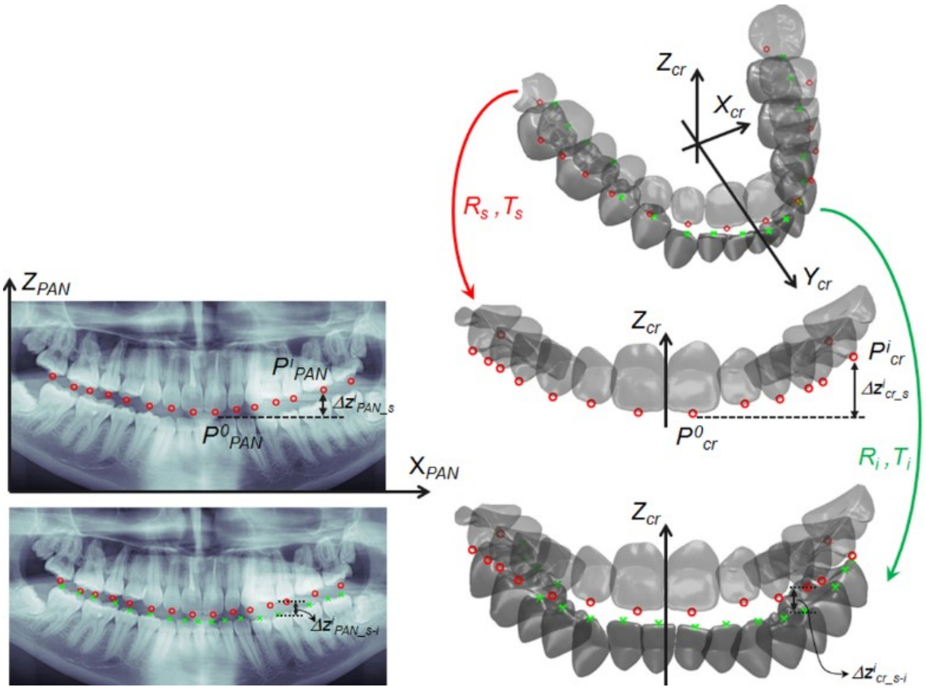


**Figure 7.** Alignment between the 3D crowns model with respect to the PAN image along the z-direction.

An additional transformation is then required in order to refer the inferior arch with respect to the transformed superior arch. The objective function to be minimized can be expressed as:

$$f(R_i,T_i)=\sum_{i=1}^{n}\left\|\Delta z^i_{PAN\_s-i}-\Delta z^i_{cr\_s-i}\right\|^2 \tag{2}$$

where $\Delta z^i_{cr\_s-i}$ represents the distance along the $Z_{cr}$ direction of the $i$-th point of the inferior arch from the nearest corresponding point onto the transformed superior arch, while $\Delta z^i_{PAN\_s-i}$ represents the distance between the pair of corresponding points onto the PAN image.

The $R_s$, $R_s$ and $R_i$, $R_i$ transformations refer the 3D crown models to the vertical direction $Z_{PAN}$ of the actual PAN image.

### 3.3.2 DRT projection model for horizontal referring

A further transformation is then required in order to project the 3D crown models onto the panoramic image. This process is accomplished by computing multiple parallel-beam projections, from different angles, using the DRT. The procedure can be summarized in the following steps:

- 3D crown models slicing;
- determination of the projection curve $\gamma$ and the projection angle $\theta$;
- DRT projection.

Once the 3D crown models have been vertically aligned with respect to the PAN image, a slicing process along the $Z_{cr}$ direction is performed with the same vertical resolution of the PAN image in order to simulate the radiograph capturing process (Figure 8-a). For each slice $S$, the intersection ($\Gamma$) between the slice plane and the 3D model is computed and a 2D binary image ($I_S$) (Figure 8-b) is created accordingly to:

$$I_S(x,y)=\begin{cases}1 & if \quad (x,y)\in\Gamma\\ 0 & otherwise\end{cases} \tag{3}$$

A single image ($J$) is then obtained by summing up the stack of slice images:

$$J=\sum_{S=1}^{PAN_h} I_S \tag{4}$$

Figure 8-c shows the image $J$ with the superior and inferior dental arch geometries evidenced with two different colors (blue and red for the inferior and superior arches, respectively). This image is used to estimate both the projection curve $\gamma$ and the angle $\theta$, which are used for the DRT projection process.

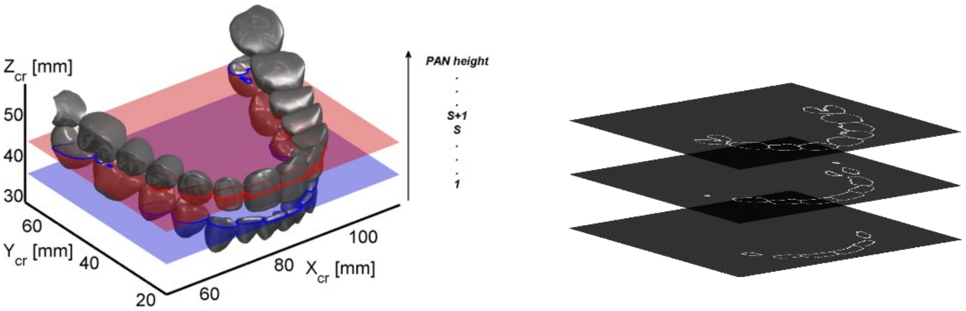
A set of points is interactively selected on the image $J$ in correspondence of adjacent tooth areas for both the superior (red circles) and the inferior arch (blue crosses). The selected point path approximates the medial axis of the crown arches. The projection curve $\gamma$ (black line of Figure 8-c) is defined as a fourth order polynomial determined by best fitting the data set through a least-squares minimization of the error term, $\varepsilon$:

$$\varepsilon = \sum \left( ax^4 + bx^3 + cx^2 + dx + e - y \right)^2 \tag{5}$$

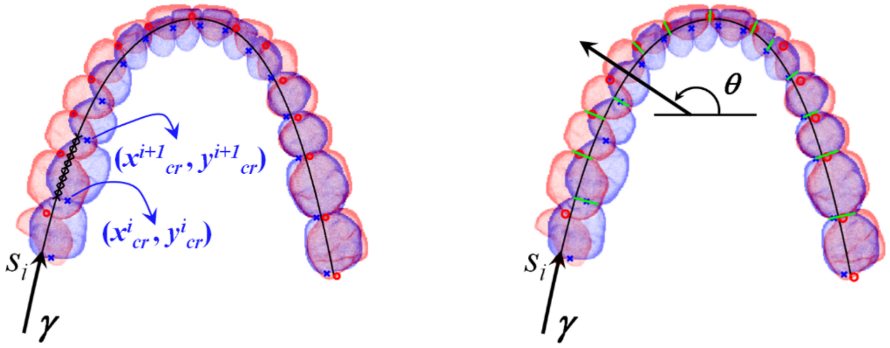
where $a$, $b$, $c$, $d$, and $e$ are the coefficients of the polynomial. The curve $\gamma$ is used to extract a set of projection points ($s_i$) by a sampling process. The crown contours of each slice are hence projected at the $s_i$ points by means of the DRT. The curve point sampling ($s_i$) is piecewisely 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.

Once the projection points have been extracted, the direction of projection, defined by the angle $\theta$ (Figure 8-d), must be determined. In this work, a sampling approach has been developed on the basis of information extracted from the actual PAN image. The direction of projection is inferred on the image $J$ (green lines of Figure 8-d) in correspondence of some adjacent tooth areas of the superior and inferior arches, where the observation of the PAN image evidences a missing, or not meaningful, overlapping between teeth. This approach provides a reasonable estimation of the projection direction occurred during the radiographic scanning process. A cubic interpolation is then performed by using the sampled estimated $\theta$ values. Figure 9 shows a comparison between the results obtained by the interpolated values and by computing the normal to the $\gamma$ curve for each $s_i$ point.

The emulation of the radiographic recording process provides the integration of crown models and panoramic radiograph along the $X_{PAN}$ direction. This process practically returns a virtual PAN image of the digital crown models, which is consistent with the actual radiographic image. Figure 10 shows the superimposition of the virtual (3D crown models) and the actual (patient's mouth) PAN images.



(a) (b)



(c) (d)

**Figure 8 -** (a) 3D crowns model slicing, (b) 2D binary images creation, (c) projection curve ($\gamma$) determination, (d) sampled estimated $\theta$ directions (green lines).

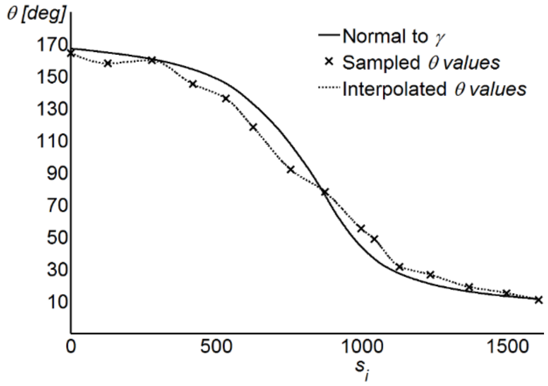


**Figure 9 -** Determination of the direction of projection ($\theta$) for the DRT.

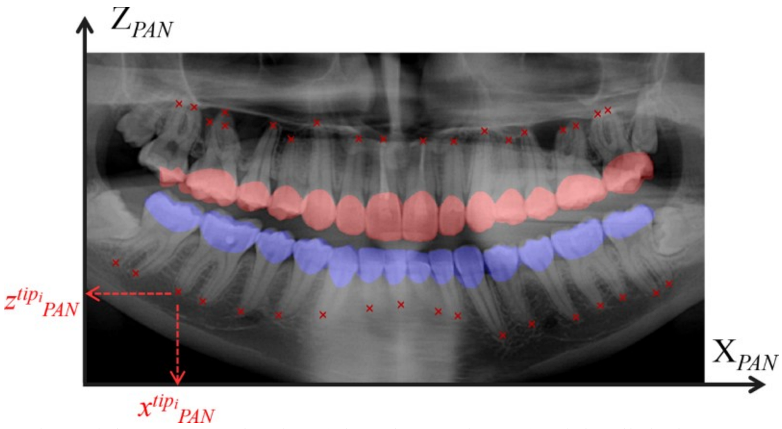


**Figure 10 -** Overlapping of the DRT projection (virtual PAN image) of the digital crown models and the actual PAN image. The root tips (red crosses) are selected on the actual PAN image.

### 3.4 Root estimation and final tooth modeling

Tooth heights are extracted from the actual PAN image by the selection of root tips (red crosses in Figure 10), which are back-projected onto the pre-scaled template models on the basis of the DRT model. The back-projection is performed by considering the coordinates of the root tip in the actual PAN image. The corresponding *z*-coordinate is used to identify the slice to which the 3D root tip belongs:

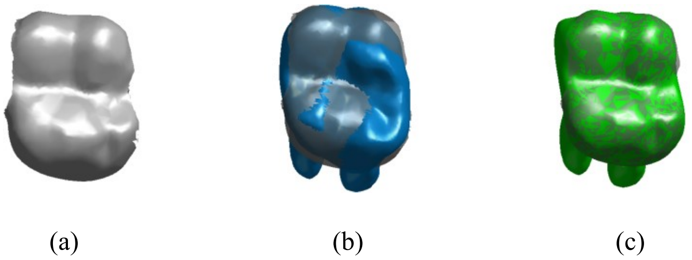
$$z_{cr}^{tip_i} = z_{PAN}^{tip_i} \tag{6}$$

The $x$-coordinate is instead used to retrieve the curvilinear coordinate along the $\gamma$ curve by:

$$s^{tip_i} = x_{PAN}^{tip_i} \tag{7}$$

Relation (7) allows the identification of the relative projection direction by interpolating the sampled $\theta$ values. The straight line through $s^{tip_i}$, making an angle $\theta$ with the horizontal axis, describes the projection ray through the root tip. This line identifies the direction along which the 3D root tip must certainly lie (*constraint line*). The CAD template tooth model, preliminarily adapted by considering width and depth values, can be finally scaled along the height direction in order to approach the above outlined constraint line. Clearly, an indetermination about the root inclination still 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's crown model guarantees the correct orientation of the reconstructed tooth.

The complete final dental shapes (green model in Figure 11-c) are modeled by merging the accurate crown data (Figure 11-a), captured by optical scanning, and the root geometries, extracted from the adapted CAD templates (blue model in Figure 11-b), through a Delaunay-based region growing (DBRG) algorithm [21]. The geometrical models are optimal references for the design of customized crown-fitting appliances. Moreover, the entire dental shapes establish a valid support for the biomechanical prediction of orthodontic movements.



(a) (b) (c)

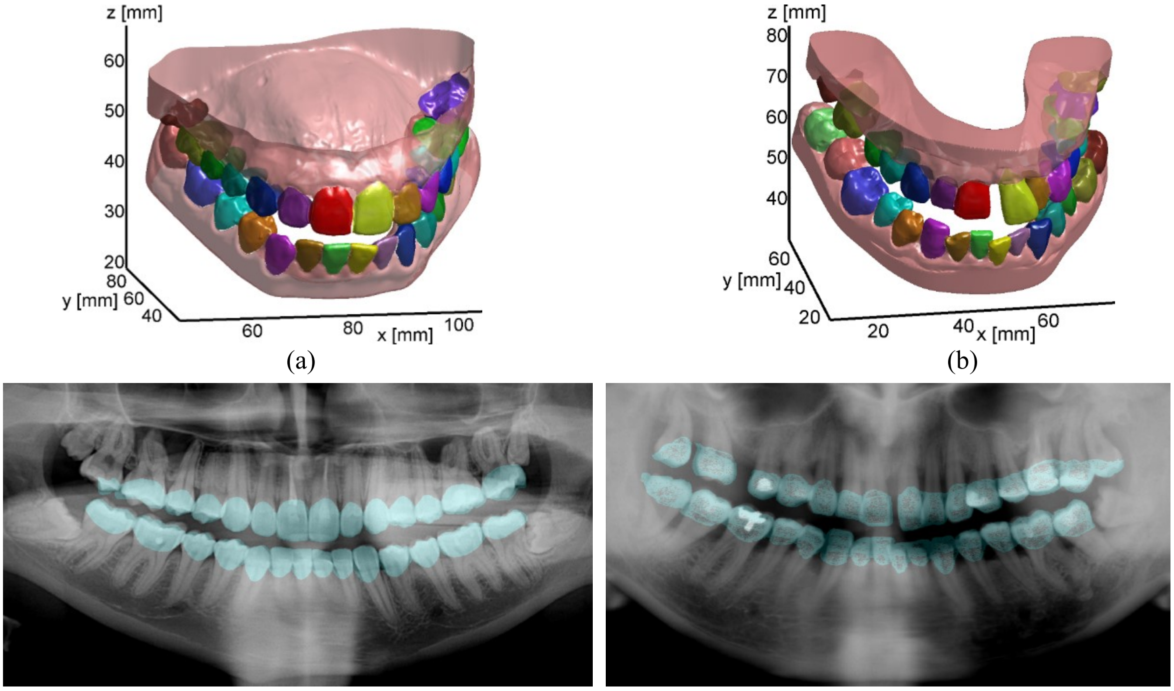
**Figure 11 –** Example of a crown geometry captured by the optical scanner (a), the adapted tooth template (b) and the complete final dental shape obtained by the merging process.

## 4. Results and discussion

The proposed methodology has been experienced in modeling dental arches of different patients. CBCT scans of the same patients have also allowed the reconstruction of dentition structures through segmentation processes performed with 3D Slicer [22], an open-source software for image analysis. Tooth geometries obtained from CBCT data have been used as ground truth to assess the accuracy of 3D models created by the developed methodology.

As examples, Figures 12-a and 12-b show the 3D models of dental arches as obtained by scanning the plaster models of two different patients, hereinafter named Patient $\alpha$ and Patient $\beta$, respectively.

The 3D representations include crowns separated from soft tissues and segmented into individual shapes. Figures 12-c and 12-d report the results of the integration of patients' crown models shown in Figures 12-a and 12-b, respectively, with the corresponding actual PAN images. The substantial overlapping between the DRT projections (virtual PAN images) of the coronal surfaces (highlighted with a transparent cyan color) with the crown regions of the radiographs allows the assessment of both the vertical alignment process between plaster casts and PAN images, and the DRT projection model. However, no information about the accuracy of root placement, which is mainly dependent on the projection angle $\theta$, can be directly deduced. For this reason, the whole dentition structures, obtained by segmenting CBCT data, have been re-projected on the corresponding PAN images by using the developed procedure. Figures 13-a and 13-b show the overlapping between the two different imaging modalities, i.e. CBCT and PAN, for Patient α and Patient β, respectively. These comparisons allow a graphical evaluation of the robustness of the DRT projection model as applied to complete dental anatomies.



(a) (b)

(c) (d)

**Figure 12 -** Segmented tooth crown models captured by the optical scanner and integration of actual and virtual PAN images of the crown models, for Patient α (a,c) and Patient β (b,d), respectively. Re-projected coronal structures have been highlighted with a cyan transparent color.

An example of the results obtained by the CAD templates adapting process for Patient β is illustrated in Figures 14. The dental templates are aligned on the crowns model (Figure 14-a) and scaled along the tooth heights directions in order to intersect the root tips with the respective constraint lines (red lines for the superior arch and blue lines for the inferior arch, Figure 14-b). Crown geometries, acquired by the optical scanner, and root geometries, estimated by scaling CAD templates, can then be merged together to create the final digital tooth models, thus preserving the accuracy of the optical scanner in the reconstruction of occlusal information.

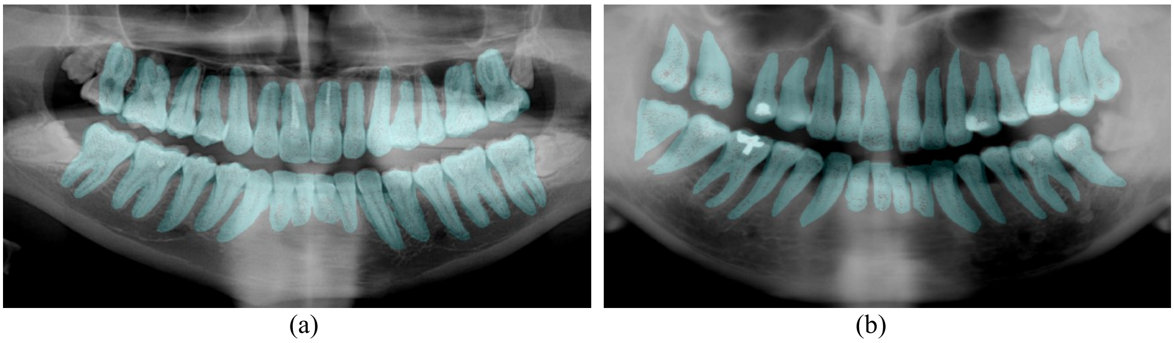

(a) (b)

**Figure 13 -** Integration of actual and virtual PAN images of CBCT segmented tooth models for Patient α (a) and Patient β (b), respectively. Re-projected CBCT dental structures have been highlighted with a cyan transparent color.

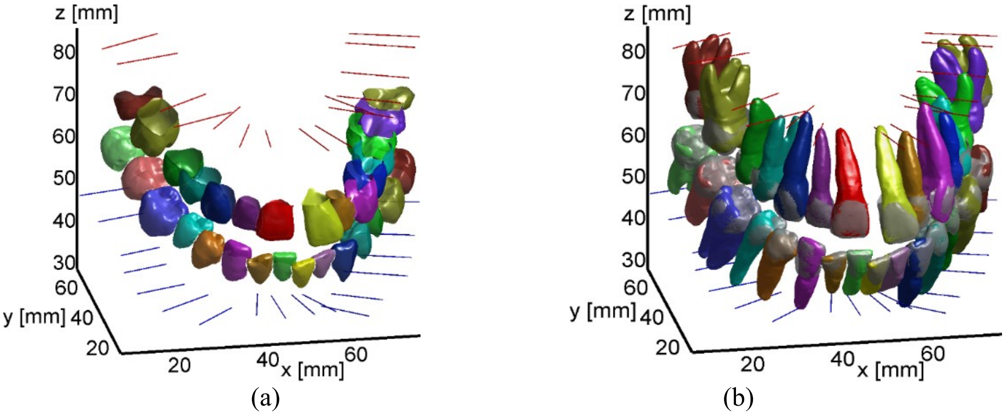
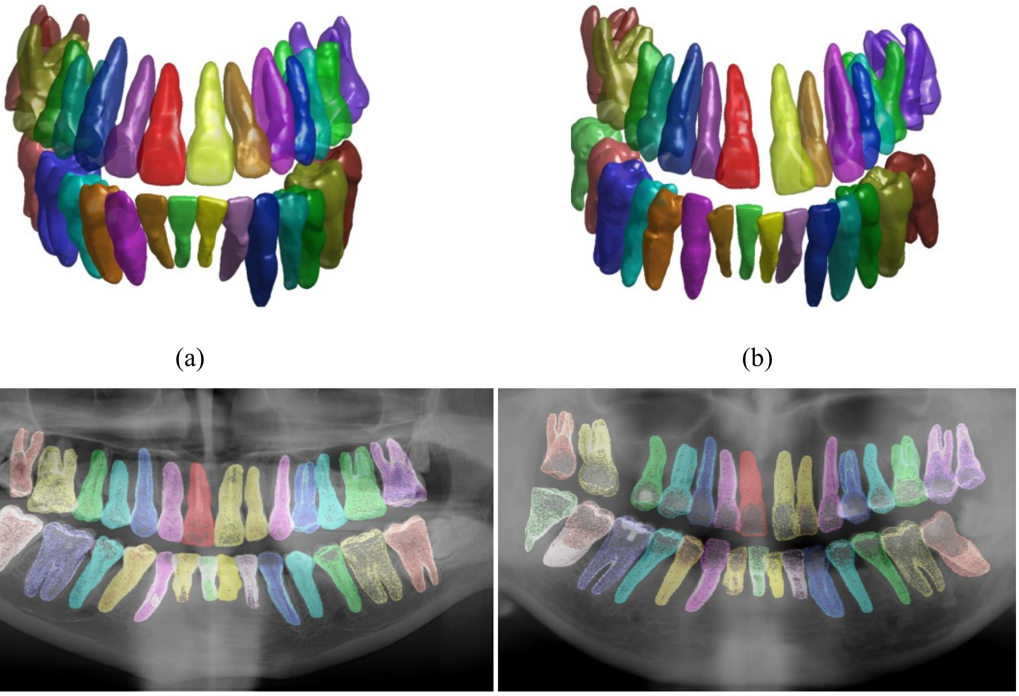


**Figure 14 -** (a) Individual crowns geometry with corresponding constraint lines, (b) CAD templates adapting process on the crowns model by using the constraint lines.

Figures 15-a and 15-b show the results of the merging process for Patient α and Patient β, respectively, while Figure 15-c and Figure 15-d report the corresponding integration between actual PAN images and virtual PAN images obtained by performing the DRT projection on the adapted templates.

The presented qualitative results have been also numerically validated by carrying out a comparison between dental shapes reconstructed by the proposed methodology and ground truth models obtained by segmenting the corresponding CBCT data. In particular, discrepancies for root tips and centers of mass of each individual root have been evaluated. Within orthodontic treatments planning, the availability of complete tooth shapes allows a better prediction of tooth movements, which are strictly dependent on the root geometrical attributes. In this context, the discrepancies for root tips also provide a reliable estimate of the maximum error for each individual tooth reconstruction.



(a) (b)

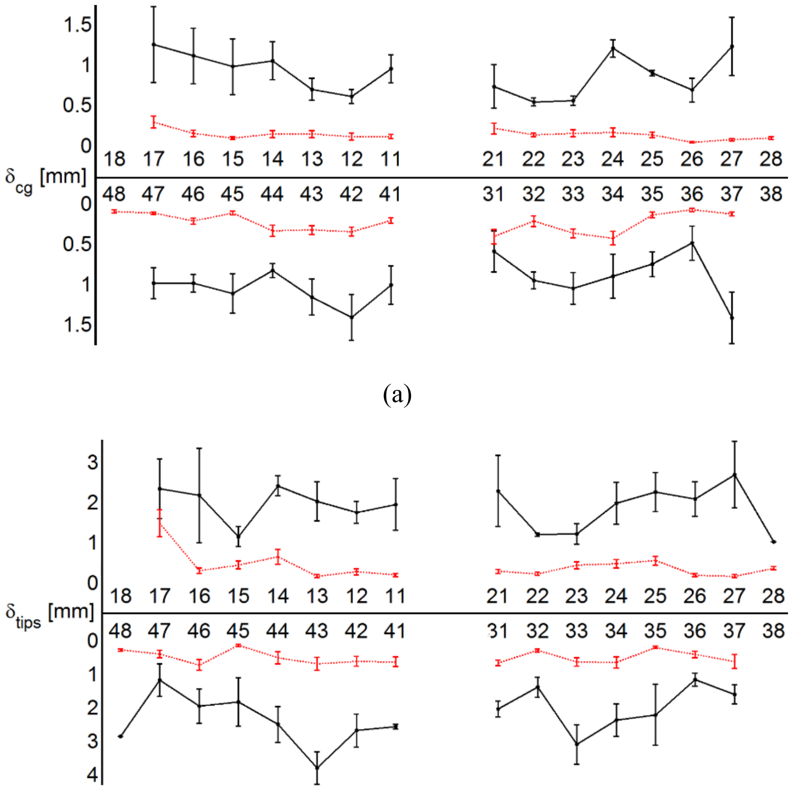
(c) (d)

**Figure 15 –** Merged tooth models for Patient α (a) and Patient β (b), respectively, along with the corresponding integration between individual adapted templates and actual PAN images.

Figures 16-a and 16-b report the graphical representations, through error bar plots, of the discrepancies variability for the centers of mass ($\delta_{cg}$) and the root tips ($\delta_{tips}$), respectively, between reconstructed and ground truth teeth. In particular, five different patients' dentitions have been experimentally estimated. Ground truth data have been defined by averaging values obtained by three different operators. For each tooth, the height of the error bar, which is centered on the mean value, is represented by the standard deviation value. Figures 16-a and 16-b also report the variability of the ground truth data by using the same error bar representation (dotted red lines).

Tooth numbers have been assigned in accordance with the ISO 3950 notation [23]. Teeth are symmetrically arranged within the mouth. Each quadrant hosts eight different teeth, which are horizontally and vertically mirrored with respect to the other quadrants. Each of these 8 teeth is numbered from 1 to 8, starting from the center front tooth (central incisor) and moving backwards up to the third molar (number 8). Moreover, a number is assigned to each quadrant: from 1 to 4 for the adult (permanent) teeth or 5 to 8 for the baby (primary or deciduous) teeth. The combination of the quadrant number and the tooth number provides a two-digit code, which unambiguously identify each tooth.

Higher discrepancies between ground truth data and teeth shapes obtained by the developed methodology can be observed for the root tips (2 ÷ 3 mm) with respect to the centers of mass (1 ÷ 1.5 mm). This is mainly due to the influence of the tooth orientation on the roots tips location. However, the variability in the root tips extraction by processing CBCT data is also higher due to the difficulty of accurately identifying the tooth tip during the segmentation process of DICOM slices. Clearly, these accuracies cannot be considered adequate for dental implant surgery planning. On the other hand, orthodontic treatments, whose routine approach usually does not require a CBCT scan, could take advantage by knowing root geometries even with an approximation of 1 ÷ 3 mm. An orthodontic digital model, including tooth anatomies with root information, can assist clinicians to better simulate results before treatment.



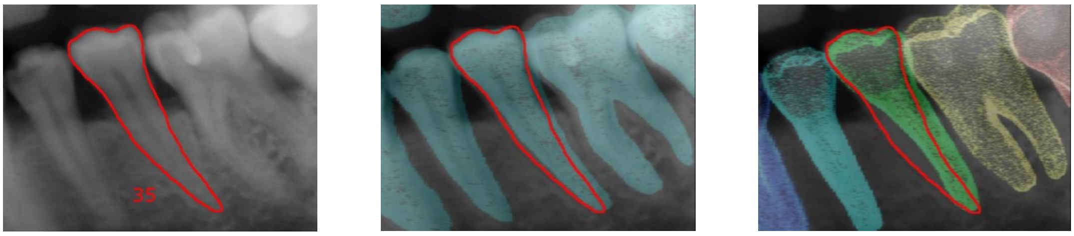
(a)

(b)

**Figure 16 -** Centers of mass (a) and root tips (b) discrepancies between reconstructed teeth and CBCT ground truth data.

It is also worth remarking that observed differences may be due to the template shapes. The use of a limited tooth library can lead to morphological differences between real anatomies and obtained tooth shapes which are not dependent on the developed reconstruction methodology. For instance, Figures 17 show the results obtained in the reconstruction of tooth 35 of Patient β (Figure 17-a). The overlapping between the re-projected CBCT data and the PAN image (Figure 17-b) proves the correctness of the adopted model. The re-projection of the adapted tooth template instead evidences a deviation in correspondence to the root geometry (Figure 17-c). A better boundary matching could be obtained by working with multiple templates with varying shapes for each tooth. In this case, the starting tooth template would be just selected from the multiple shapes on the basis of anatomical similarities.

The authors would like to observe that the proposed methodology is not restricted by any particular limit on the collection of anatomical data. In the present work, mouth models have been reconstructed from a plaster cast by using a structured light scanner. However, either a laser scanner or an intraoral scanner, for the direct digitization of dental structures, could have been used. Moreover, also panoramic radiographs can be acquired by any recording device, since the developed DRT projection model prescind from the hardware used



(a) (b) (c)

**Figure 17 -** Detail tooth 35 of Patient β: actual PAN image (a), overlapping of the corresponding CBCT image (b) and re-projecting of the adapted tooth template (c).

## 5. Conclusions

In the field of orthodontics, most of the treatments are planned by only considering crown data, ignoring root geometries. However, the complete information on tooth shapes, including both coronal and root anatomies, would be a valuable support to enhance treatment planning and to provide more realistic simulations. Moreover, one of the main challenges relies on the accurate determination of these geometries by exposing patients 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 feasibility of adapting general dental CAD templates over real tooth anatomies by exploiting geometrical information contained within panoramic images and digital plaster casts. The proposed modeling approach allows a generalized formulation of the problem since assumptions about the imaging device used for radiographic data capturing are not required.

Clearly, the adapting process of general CAD templates is not able to guarantee the exact match of the reconstructed root shapes and positions with the real patient dental anatomy, and the accuracy of the obtainable results is strictly dependent on the wideness of the available CAD templates library. However, even a rough estimate of the complete dental model with its inertia allows tooth gradual movement to be dynamically simulated, thus enhancing the accuracy of tooth corrections. The developed tooth modeling approach enables both crown and root contacts to be monitored, thus ensuring a comprehensive planning.

The approach involves some variables, which could suggest the direction of future studies. In particular, key issues are represented by the optimization of both the projection curve $\gamma$ and the projection angle $\theta$, whose values determine the orientation of root tip constraint lines. These topics certainly require further research activities taking also into account, for example, additional information extracted by supplementary lateral radiographs.

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