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► **To cite this version:**

Barbara Romaniuk, Michel Desvignes, Julien Robiaille, Marinette Revenu, Marie-Josèphe Deshayes. Augmented Reality and Semi-Automated Landmarking of Cephalometric Radiographs. Proceedings of 9th Computer Analysis of Images and Patterns, 2001, Warsaw, Poland. pp.410-418, 10.1007/3-540-44692-3_50 . hal-00867694

HAL Id: hal-00867694

<https://hal.science/hal-00867694>

Submitted on 30 Sep 2013

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Augmented reality and semi-automated landmarking of cephalometric radiographs

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Abstract. In this paper, we propose computer assisted visualization for manual landmarking of specific points on cephalometric radiographs. The signal to noise ratio of radiographs is very low, because of superimposing of anatomical structures, dissymetries or artefacts. On radiographs of children, the localization of cephalometric points presents a great inter-subject, and inter- and intra-expert variability, which is considerably reduced by considering an adaptative coordinates space. This coordinates space allows us to obtain statistical landmarking of cephalometric points used to define regions of interest. Each region takes advantage of a specific image processing, to enhance local and particular features (bone or suture). An augmented reality image is presented to the human expert, to focus on main sutures and bones in a small region of interest. This method is applied to the nettlesome problem of the interpretation of cephalometric radiographs, and provides satisfying results according to a cephalometric expert.

Keywords

Statistical Shape Model, Augmented Reality, Cephalometry.

1 Introduction

The goal of cephalometry is the study of the skull growth of young children in order to improve orthodontic therapy. It is based on the landmarking of cephalometric points on radiographs, two-dimensional X-ray images of the sagittal skull projection [2]. These points are used for the computation of features, such as the length or angles between lines. The interpretation of these features is used to diagnose the deviation of the patient form from the ideal one [5]. It is also used to evaluate the results of different orthodontic treatments [3] [9]. However, the anatomical definition of cephalometric points is difficult to apply directly on radiographs. The landmarking is hard and an important inter- and intra-expert variability is to be noticed. It is necessary to reduce this variability.

Cephalometric points are usually precisely defined in relation to skull and bones which are three-dimensional objects. Unfortunately it is sometimes impossible to apply directly these definitions on radiographs, which are bidimensional projections of the three-dimensional object. Most cephalograms are defined as an intersection between bones and sutures; this appears as a curvilinear white (bone) and black (suture) structure on the radiograph. They are often difficult to locate because of the superimposition of many other bones on the 2D projection of the radiograph [6], and the definition of cephalometric points is specific for each point: we must decompose the problem into many sub-problems, specific to each landmark.

The goal of this work is a computer assisted landmarking using augmented reality. On a cephalogram, a small region of interest is automatically defined for each cephalometric point. The contrast of this region is modified to enhance feature used to locate cephalometric points. These regions are the support for manual landmarking of cephalometric points on radiographs by experts.

The first step of the work consists in finding a coordinates space that will evolve with the shape, the size and the orientation of each skull. The inside outline of the skull is the main component of this coordinates space because of its adaptivity to the morphology of each patient [8]. The second step is the statistical landmarking of cephalometric points. Training has been done on 58 samples which provide statistical coefficients used to determine the statistical position of cephalometric points. On new radiographs, the statistical landmarking of cephalometric points gives an approximation of the final position of the points. Using the standard deviation of the position, we defined small regions around each cephalometric point. Some of the points, with the help of the expert, are gathered, allowing the definition of regions of interest. The regions of interest contain the cephalometric points as well as anatomic structures, that the expert needs for landmarking. For each region of interest, we use augmented reality to enhance the contrast of the main structures used to locate the cephalometric landmarks.

In the first part of this paper we will present the automatic localization of regions of interest that is composed of the definition of the coordinates space, the statistical landmarking of cephalograms, and the definition of regions of interest. The second part deals with the augmented reality process in the standard case for the first and sixth regions. Lastly the results and conclusion of our study will be presented.

2 Automatic localization of regions of interest

2.1 An adaptative coordinates space

The idea is to extract a simple form that could characterize the dimensions of the skull. Then we decide to consider the internal surface of the skull (endocranial contour) that will bring us a simple numeric model for the position and the form of the skull.

The main problem of the contours detection is the difference of the intensity of contours which depends on the regions in which they lie. The bone parts of the superior part of the skull are more pronounced than those located in the vicinity of the sphenoid, where the low contrast makes the detection difficult.

Deriche's gradient is used to detect edges [4], and the endocranial contour is detected by active contours, based on the Cohen's model of balloons [1]. The result is visible on Figure 1. The curve (endocranial contour) is sampled by only 16 points. The first point is the one with the higher curvature, that is near the intersection of the curve and the nasal bone. This point is stable, *i.e.* it is always present in the same area of any image. The other 15 are regularly distributed on the endocranial curve, starting with the point of maximal curvature. 5 points are also considered: the isobarycenter of all the points of the endocranial curve, and the 4 corners of the smallest rectangle containing the curve. Figure 2 presents those 21 points.



Fig. 1. Endocranial contour detection **Fig. 2.** Sampled endocranial contour

Let ζ be the set of vectors :

$$\zeta = \{(O_i, \vec{v}_i) \mid \forall (j, k) \in \{1..n\}, j < k, \exists i \text{ such as } O_i = P_j \text{ and } \vec{v}_i = \overrightarrow{P_i P_k}\} \quad (1)$$

The points P_i are the characteristic points extracted from the endocranial contour curve. We then obtain the set of $p = n(n - 1)/2$ couples, made of one point and a vector. ζ is the set of all vectors that can be made between the characteristic points. For the given point M , we define the set of parameters $\{\alpha_1, \dots, \alpha_p\}$ in the following equation :

$$\alpha = \langle \overrightarrow{OM} \mid \vec{v} \rangle \quad (2)$$

The passage from the cartesian coordinates to the set of $\{\alpha_1, \dots, \alpha_p\}$ can be written as a linear system. We define the vector X that represents the point M using homogeneous coordinates. Then we obtain :

$$X = \begin{pmatrix} M_x \\ M_y \\ 1 \end{pmatrix} \quad (3)$$

The computation of the coefficient α_i , associated to the couple $(O_i, \vec{v}_i) \in \zeta$ can be written as the equation :

$$\alpha_i = (v_{ix} \quad v_{iy} \quad - (O_{ix}v_{ix} + O_{iy}v_{iy})) \begin{pmatrix} M_x \\ M_y \\ 1 \end{pmatrix} \quad (4)$$

Then, when we have the set ζ , we can associate to every point M its parameters α_i by the matrix multiplication $\alpha = AX$.

The coordinates α_i are the projection of the point M on each vector built using the endocranial contour. This system of coordinates allows every point of the cephalometric radiograph to evolve with the shape and the morphology of the patient. This is our coordinate space.

2.2 Statistical landmarking of cephalograms

The method of global landmarking of cephalometric points is based on the estimation of the mean value of α , $\hat{E}[\alpha]$, on a training set of evaluated radiographs, where we know the exact position of the cephalometric point. Then, when we analyse a new radiograph, we assess α by $\hat{E}[\alpha]$.

This estimation is made on a training set of 58 evaluated radiographs. We know how to determine the set ζ by means of the endocranial contour. This allows us to find the matrix A . To locate an unknown landmark Y on a new radiograph, we need to inverse the system $\hat{E}[\alpha] = AY$

The resolution of this system is obtained by using a modified version of the least squares method. The idea is to consider the variance $\sigma_i = \hat{E}[(\alpha_i - \hat{E}[\alpha_i])^2]$ as a balancing coefficient. Indeed, if the variance $\hat{\sigma}_i$ of the coefficient α_i remains low during the calculation of $\hat{E}[\alpha]$, it means that the information contained by this coefficient is more precise than the one contained by another coefficient, with a higher variance. We introduce the ponderation matrix:

$$P = \begin{pmatrix} \frac{1}{\hat{\sigma}_0} & 0 & \dots & 0 \\ 0 & \frac{1}{\hat{\sigma}_1} & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \frac{1}{\hat{\sigma}_p} \end{pmatrix} \quad (5)$$

The cost function in the least squares inversion becomes: $J = \| P\hat{E}[\alpha] - APX \|^2$, because not every coefficient has the same importance in the resolution.

Finally, we will only retain the highest coefficients of P , and the others will take the value 0. Only 20 coefficients are kept, because the cost function is minimum for this number.

The position of the unknown landmark X is given by the equation:

$$\hat{X}_{MC} = (A^t P^t P A)^{-1} A^t P^t \hat{E}[\alpha] \quad (6)$$

When we want to compute the position of a point on a new cephalometric radiograph, we compute the adaptative coordinates space. In this way we obtain the vectors \vec{v}_i^t that define the internal surface of the skull. Then we may compute the matrix A , and finally solve the equation (6) that gives us the coordinates of the landmark.

2.3 Regions of interest

The next step in this study is the definition of regions of interest. This definition is based on a statistical analysis of landmarking of cephalometric points computed in the previous phase.

The windows of interest are radiography regions. They gather some cephalometric points and structures (bone or suture), that are necessary for a good localization of a cephalometric point by a human expert. Six regions of interest have been defined by an orthodontist and an image processing expert. For example, to find the real position of the point M , we need the direction of the ascending branch of the maxillary. Then the window number one contains three cephalometric points and the ascending branch of maxillary.

The statistical position of cephalometric points allows us to compute the errors between the computed position and the real position obtained by the expert. The computation is done on the training sample of radiographs. The standard deviation is computed between the statistical coordinates and the expert coordinates according to the X-axis and the Y-axis. The limits of the windows use the standard deviations previously computed on the training sample. Assuming gaussian hypotheses for the distribution of the position, a cephalometric point is located in a three standard deviation radius (according to the X-axis, and the Y-axis) from the statistical location of this point with an error of 0.5%. This area delimits the probability zone for every cephalometric point.

The limits of the regions of interest require the definition of the probability zone of every cephalometric point they contain. The frontiers of those probability zones are then used to delimit the final interest windows. Figure 3 presents an example of the first window. The three white frames represent the probability zones of the three cephalometric points included in the first region of interest. On this image, the extreme frontiers 1, 2, 3 and 4, of the three probability windows are used to define the frontiers of the final window. These frontiers are adjusted by some expert constraints. For example, in the first window, the orthodontist needs the direction of the ascending branch of the maxillary to find the right position of cephalometric points: the height of this window is then increased. The 14 points require six windows that contain between one to four points to locate. Figure 4 represents the result of an automatic localization of these windows on the radiograph.

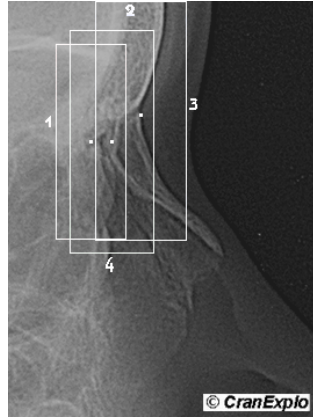


Fig. 3. Probability zones used to define the final interest window

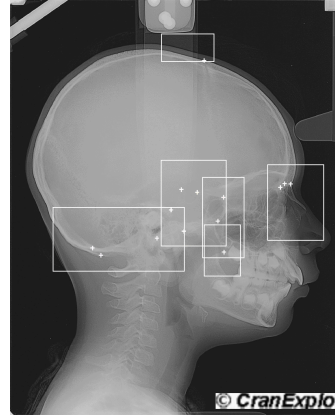


Fig. 4. Automatic localization of interest windows on a radiograph

3 Augmented reality

3.1 Standard processing

The next step is to provide a better visualization to help the orthodontist in the labelling of cephalometric points. It is implemented by the enhancement of the main structures that are needed to locate each cephalometric point [7].

Each of the regions of interest present different particularities, consequently every window will take profit of a specific processing. The windows contain much visual information, but only a few of them are important during the localization. Thus, we try to have these information more visible. The window one and six take profit of very specific treatments. The others present the same characteristics and a very simple treatment was judged satisfactory by the human expert. This treatment is a histogram equalization.

3.2 First region of interest

The ascending branch of maxillary, which is a black structure on the radiograph, has to be enhanced. The solution of this problem requires the detection of thin lines, and the enhancement of the contrast in the regions which contain black small structures [6].

For the detection of fine curves, we compute the Deriche's gradient image. This image contains the fine structures that we want to detect, but also noise. This noise is the result of soft tissue and useless structures. To eliminate this additional information, we apply a hysteresis thresholding on the gradient image. The lower threshold is equal to two standard deviations computed on the first interest window in the gradient image. The higher threshold equals three standart deviations.

All contour chains that are no longer than three pixels are eliminated. Those chains can not be considered as the ascending branch of the maxillary, which is a thin and long curve.

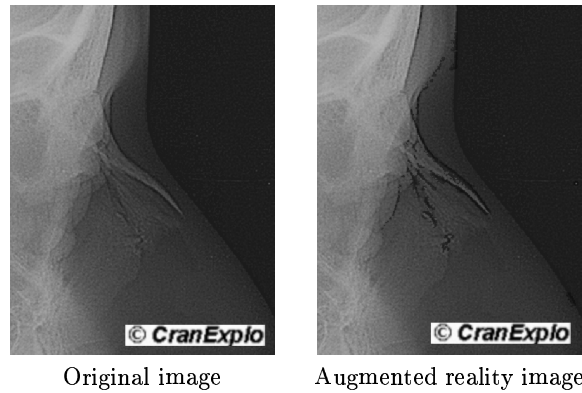


Fig. 5. Results obtained for the first region of interest

Finally, the treated gradient image is superimposed on the original one. Pixels of the detected contour (i.e. the maxillary) are set to 0, as well as their neighbours, other values are unchanged. We then obtain the augmented reality image, with the ascending branch of maxillary. Figure 5 presents the results obtained.

3.3 Sixth region of interest

The fronto-parietal suture, which is usually undetectable, has to be enhanced. It is located in a zone of the image, in which the cephalostat adds some information. The second problem is that this suture disappears for older children. The suture is a curvilinear structure, which appears darker than the neighbourhood. It is located on the exocranial contour, and lies towards the center of the skull. The angle between the suture and the exocranial contour is always around 60° . The detection of this suture is made using these features. The detection scheme is an iterative one: we start with a curve on the exocranial contour. Several positions of the suture are obtained by fitting an intensity model of the suture along the previously defined curve. These positions must be linked to the previously detected points, except for the 3 first iterations. The curve is then displaced toward the barycenter of the skull, and the process is iterated.

The structures detected by this method are thin, dark structures, connected to the exocranial contour. The three longest are kept by discarding all the little noisy structures. We conserve the three longest, because the cephalostat in this window often appears as two “artificial” sutures. Figure 6 presents the results obtained for the sixth window.

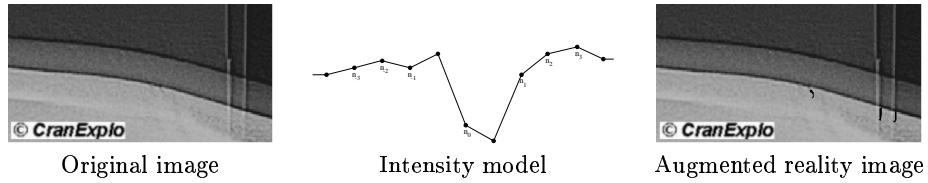


Fig. 6. Results obtained for the sixth interest window

4 Results

Landmarking

An evaluation of the error between the results of the statistical landmarking and the expert one was completed. In the region near the fronto-nasal region, in which we can find the first region, the mean error is about 4.5 mm, with the maximum error about 12.5 mm. The other regions, in which most of cephalometric points were found, the mean error is about 3.5 mm, and the maximum is reduced to 6.5 mm. The error values must be compared to intra and extra expert variabilities, which has been reported to be higher than these values.

Landmarking

The efficiency of the proposed processing for the interest windows one and six was evaluated as well. Specific image processing of windows one and six are considered as unsatisfying result, if they enhance false structures, or if they does not enhance the true structure. 90% of images of augmented reality obtained by the process of the first window give satisfying results. The proposed process for the sixth window is less efficient: only 85% of result images are interesting for the practitioner. However, the reason of these failures is often the absence of anatomical structures in the original image. Another reason of failure for the sixth region of interest can be the superimposition of the anatomical structures with the artefact (cephalostat) in the window.

5 Conclusion

This paper deals with the difficult problem of landmarking X-Ray cephalograms. We have proposed an augmented reality scheme, for computerized assisted landmarking. The first step has been to locate automatically and to design regions of interest. In these regions, a specific image processing enhances local features, and helps the practitioner to locate precisely the cephalometric points.

Our methodology allows us to obtain an adaptative coordinates space, that evolves with the growth of each skull. In this specific coordinates space, cephalometric points are statistically landmarked. Then the location leads to the deter-

mination of the windows of interest, on which the practitioner focuses. Augmented reality images are proposed to the expert, for manual landmarking of cephalometric points. The results are quite promising. Those treatments were included in a software developed by the TCI society (Cranexplo[©]). Regions of interest are also presented in a new pedagogical publication [7]. Future investigations will deal with a large database of cephalometric radiographs and with building deformable models of suture and bone to fit into the regions of interest.

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