SIMULATION OF POSTOPERATIVE 3D FACIAL MORPHOLOGY USING PHYSICS-BASED HEAD MODEL

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ABSTRACT

We propose a 3D head modeling method and a prototype of the facial surgery simulation system for surgical prediction using a physics-based head model. The arbitrary head model is reconstructed to match the target head shape by the use of anatomical measurement points plotted on the two directional X-ray images from both of frontal and side views. The accurate 3D coordinates of their points are obtained using 3D Cephalogram Measurement. For the detailed fitting of the face, the feature points automatically detected from a frontal facial image are utilized to match the facial parts such as eyes, a nose, and a mouth. These measurement points are emplogal as the control points in the model fitting process, and the other points are deformed by the smooth interpolation based on their positions relative to the control points.
In this paper, we focus on the facial surgery simulation, Orthodontic surgery. In the experiment, we predicted the facial shape after surgery for patients with mandibular prognathism. We also simulate facial dynamics before and after surgery, which is derived from both of muscular and skeletal systems. By comparing simulation results with the actual facial images after surgery, proposed method can be proved to be practically useful.

1. INTRODUCTION

1.1 Related Works

3D facial modeling is very essential for natural facial representation and the technique is utilized in several fields and applications, such as tele-conferencing, man-machine interface, and realistic human representation in the virtual reality space. In order to achieve that, some facial modeling and synthesizing methods have been proposed based on lots of ways. One of them is the physics-based modeling method. Some studies have proposed physics-based facial models based on the fact that actual facial expressions are generated by the dynamics of facial muscles underlying facial surface, considering the actual facial anatomy. Actually, some works proved their ability to create realistic facial animation [1][2][3][4]. The advantage of these physical models is that they can predict facial expressions followed by changes of facial muscles. Therefore, anatomically accurate models have been developed not only for facial animation for visual communication but also for medical applications. Regarding such a medical application, R.M.Koch developed a prototype system for surgical planning and prediction of facial shape after craniofacial and maxillofacial surgery for patients with facial deformities, using finite element models from MRI data set [5]. H.Mita et al. proposes a elaborate model including underlying facial tissue from CT scanned data for a facial paralysis simulator [6]. These works show the postoperative facial morphology by the computed 3D facial image, however, the evaluation of the results is still not satisfactorily done because of the insufficiency of patients' data.

1.2 Motivation

In this paper, we propose a head model reconstruction method from CT and X-ray images. The facial surgery simulation system is also described using this anatomical and physics based head model. Main feature of our head model is that it can analyze facial dynamics by calculating the kinetic equation for entire physical statement. As a practical example of medical applications, we focus on the facial surgery simulation for orthodontics. Concretely, we investigate the relationship between changes of the mandibular position and that of the facial morphology after the orthognathic surgery is carried out, and simulate the exact postoperative 3D facial deformation by the use of the physics-based head model. In terms of the actual treatment and surgery of dentistry, to predict the result in advance is extremely important for both of dentists and patients. Therefore, we aim at the facial surgery simulation system that assists surgeons in surgery planning and actual surgical procedures visually, by the 3D display of realistic and accurate predicted results with visualization using computer graphic technique.

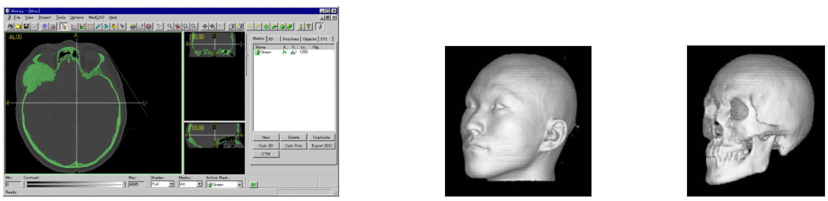
We organize this paper as follows: In section 2, we describe the proposed head model and its dynamical mechanism. In section 3 and 4, we describe feature extraction from X-ray images and facial images, and explain how to deform the generic head model to match the target head. Next, we demonstrate our surgery simulation system in section 5. We show some simulated results using actual patients' data, and evaluate experimental results compared with the actual surgical cases in section 6. Finally, we conclude this paper with some future works.

2. INITIAL HEAD MODEL

2.1 Modeling method

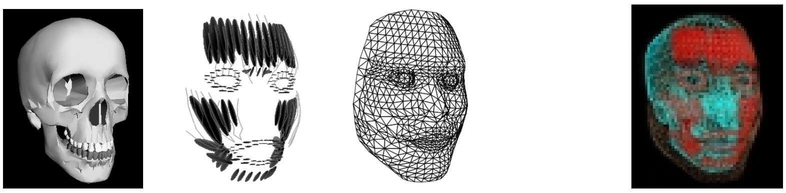
We constructed the hierarchical head model that consists of a skin layer, a muscle layer, and a skull layer. The skin and skull layers are segmented from 3D CT data by thresholding, using medical data software called “Mimics”.

The skin layer is a wire-frame model constructed from CT scanned data, which is regarded as an elastic body. All frames composed of the skin are simulated by non-linear springs that can represent the skin elasticity by their elastic parameters. The facial muscles are also modeled by non-linear springs, which start from the skull layer and are attached to facial surface just like the actual facial structure. The muscles are grouped by their position, and act with connected facial tissues in harmony. In the present, 14 kinds of facial muscles are simulated which are mainly concerned with facial expressions. Each muscle has the contraction parameter to generate facial expressions. For the skull layer, the polygon model from ViewPoint Corp. is used. The jaw part of this model can simulate realistic jaw movement with six degrees of freedom and it is located under facial tissues referring the relation ship between the face and skull. Three layers composed of the hierarchical head model and integrated head model are all illustrated in Figure 2. This generic head model is used as the initial head model for the head reconstruction process.



(a) “Mimics” (b) Segmented Face (c) Segmented Skull

Figure 1. Data extraction from 3D-CT



(a) Skull (b) Muscles (c) Skin (d) Integrated model

Figure 2. The generic head model

2.2 Dynamical facial mechanism

In generating facial expressions, points on the skin model are moved in order to obtain the modified face. The energy of the spring system can be changed by both of muscles' contraction and the jaw action, and the new position of each point on the facial surface is obtained by calculating the energy equilibrium point of the entire spring system. The kinetic equation for feature point i on the facial surface is given as following eq.(1).

$$m_i \frac{d^2\boldsymbol{r}_i}{dt^2} = -\sum_{i,j} k_{ij}(c_r)\left(\boldsymbol{r}_i - \boldsymbol{r}_j\right) + m_i\boldsymbol{g} - R\frac{d\boldsymbol{r}_i}{dt} \tag{1}$$

Where r_i represents the 3D coordinates of the feature point *i*. The first and second terms represent the total elastic force affected to the point *i* and the attraction of gravity, respectively. The value of k_{ij} is changed gradually by the contraction parameter *Cr* of each spring so that it can represent the skin and muscles' non-linear property. The third term is the viscous term of the facial model.

Figure3 shows the result of generating the typical facial expression “surprise”, which is caused by the muscles' contraction around forehead and jaw rotation. Thus, our head model can create flexible facial expressions derived from given parameters, such as contraction rates of muscles and action parameters for the jaw so that facial dynamics can be simulated.

(a) Muscular and skeletal action (b) Facial surface modification

Figure 3. Facial expression

3. SHAPE FEATURE EXTRACTION

In this section, we describe shape feature extraction method required to deform the generic head model to fit the target head. To obtain three-dimensional shape information of a face and a skull, two-directional X-ray images and a frontal facial image are used in our method. The high resolution volume data can be obtained using 3D-CT, however, it has a high risk of radiation and the costs is high as well. For this reason, we integrate feature information from both of a facial image and normalized X-ray images that are ordinarily captured for orthognathic diagnosis.

3.1 Measurement Points Extraction from X-ray Images

3.1.1 Measurement Points. Anatomical measurement points on a face and a skull are usually utilized in order to analyze their shape quantitatively in orthodontics. Based on this analysis, orthodontists plan how to treat in each case of a patient by reconstructing 3D shape from images. Figure4 shows the plotted measurement points on the sketches of X-ray images (cephalograms) from both of frontal and side views. Each position of measurement points is defined in detail, especially the point on the contour which has large curvature. We manually plot on the two-directional cephalograms by mouse operations, and use them as the typical control points of the head. The number of measurement points is 22 for a skull model, and 21 for a face, respectively.

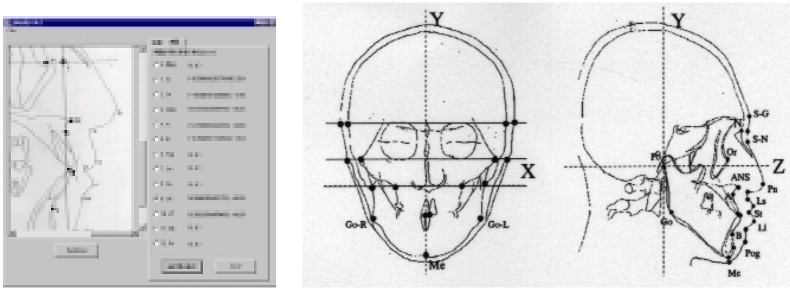
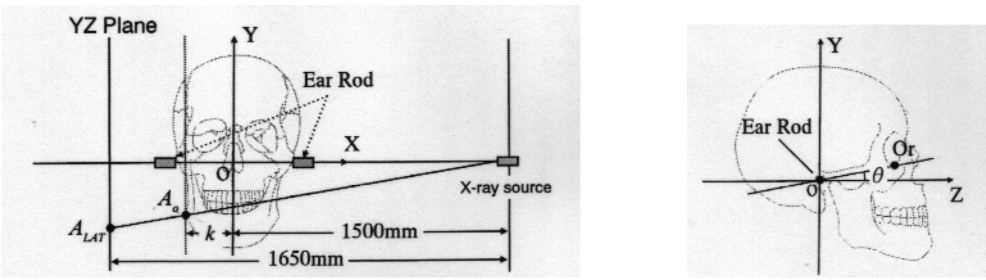


Figure 4. Plotted measurement points on the cephalograms

3.1.2 3D Cephalogram Mesurement. From the 2D coordinates of each point on the two-directional cephalograms, the 3D coordinates can be calculated by integrating them. However, a target object is usually projected onto the image planes as expanded and rotated images, as shown in Figure 5.



(a) Projection onto YZ image plane (b) Head orientation around horizontal axis

Figure 5. Adjustment required to obtain 3D coordinates

In capturing X-ray images, a head is fixed by the ear rods. Two x-ray sources and cameras are also bound, so we can obtain both of normalized facial images and x-ray images from frontal and side views. The head is projected onto the picture planes as expanded images of actual measurement. Therefore, the expansion adjustment should be considered to obtain an accurate 3D shape of the head. As shown in Figure 5, the point on the subject A_o (x_o, y_o, z_o) is enlarged and projected as the point A_{LAT} (y_{LAT}, z_{LAT})on the picture plane (YZ plane). The coordinates of the measurement point A_o can be computed by following adjustment eq.(2). The value of k is the distance from Y axis, so that it depends on each measurement point.

$$y_o = y_{LAT} \times \frac{1500+k}{1650}, \quad z_o = z_{LAT} \times \frac{1500+k}{1650} \tag{2}$$

Although the head is fixed by the ear rods, slight head rotation around horizontal axis is unavoidable in capturing images so that the measurement point on the subject is projected to the incorrect position (x_{PA}, y_{PA}) on the XY plane. The rotation adjustment can be calculated by eq.(3). Then, the line (y=y_{PA}) is drawn on the frontal cephalogram, and the exact value of x_{PA} is obtained by the cross section with the skull and facial contour using eq.(4). Thus, the accurate 3D coordinates of the measurement point (x_o, y_o, z_o) can be ready for the face reconstruction process.

$$y_{PA} = \frac{1650\,(1500+k)\left(z_{LAT}\sin\theta + y_{LAT}\cos\theta\right)}{1500\times 1650 + (1500+k)\left(z_{LAT}\cos\theta - y_{LAT}\sin\theta\right)} \tag{3}$$

$$x_o = x_{PA} \times \frac{1500 + z_o}{1650} \tag{4}$$

3.2 Feature Points Extraction from a Frontal Facial Image

From two directional X-ray images, rough profiles of the head can be extracted. For more detailed fitting of the face shape, we use facial feature points on the contours of facial parts (eyes, nose, mouth). The facial feature points are automatically detected by the combination of several recognition techniques; Skin color extraction to detect the facial area, the template matching in the facial area to find the locations of pupils, and the active contour model to extract the contours of facial parts. Figure 6 indicates automatic recognition results using normalized frontal facial images of patients before treatment. The facial feature points are well recognized in each case. This is partially refined software developed by IPA[14]. Using these data, the detailed fitting of a face model can be realized automatically.

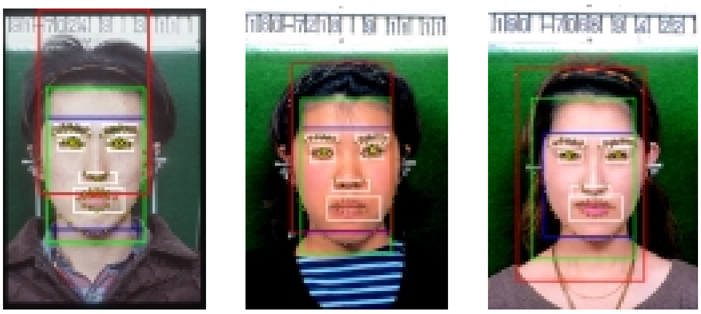
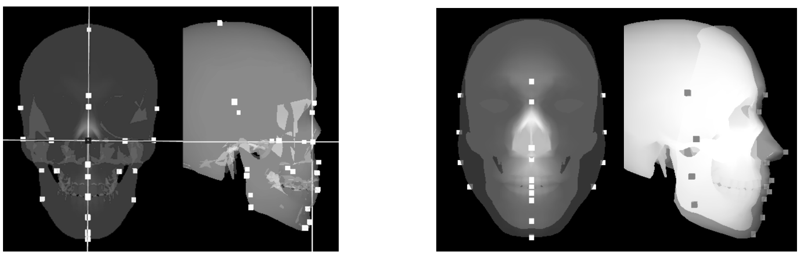


Figure 6. Detected feature points on the frontal facial images

4. DEFORMATION OF THE MODEL

4.1 Corresponding Points on the Head Model

In order to deform the generic head model according to obtained 3D coordinates of measurement points, we should also set the corresponding points on the head model. We selected the corresponding points as shown in Figure 7.



(a) Skull (b) Face

Figure 7. Corresponding points selected on the head model

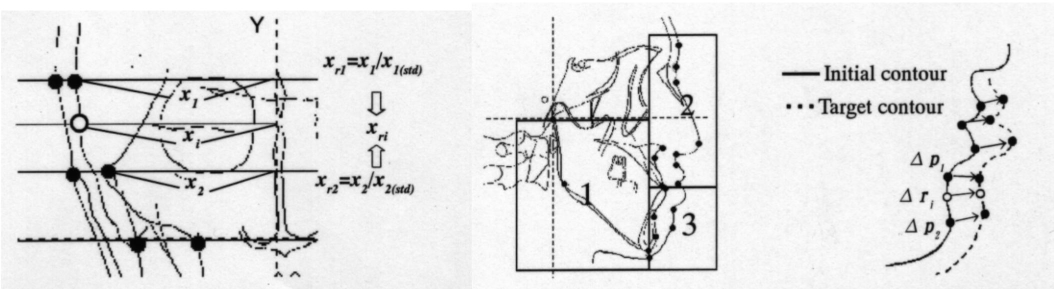
Using the width measured from frontal image (x_1, x_2) and the corresponding width of the initial head model ($x_{1(std)}$, $x_{2(std)}$), rates of the width are calculated so that the x coordinate of the point i is computed by the linear interpolation eq.(5) (See Figure 8). S_n represents the number of steps between point *1* and *2*. After width and height fitting, the coordinates of (y_o, z_o) is used for the fitting of depth and height directions. The whole head is divided into 3 parts, back part and frontal parts (upper and lower) as shown in Figure 8, considering anatomical structure of a head. The movement vector of each measurement point is calculated, and rest of the points between two measurement points are computed by the linear interpolation eq.(5).

$$x_{ri} = \frac{i\, x_{r2} + (s_n - i)\, x_{r1}}{s_n} \quad , \quad \Delta \boldsymbol{r}_i = \frac{i\, \boldsymbol{p}_2 + (s_n - i)\, \boldsymbol{p}_1}{s_n} \tag{5}$$

$\Delta \boldsymbol{r}_i$: The movement vector of the point i

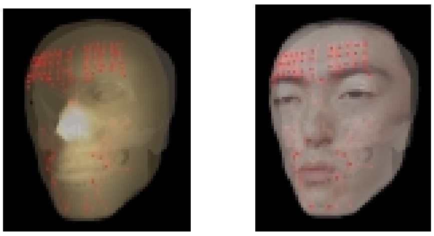
$\boldsymbol{p}_1, \boldsymbol{p}_2$: The movement vectors of measurement points

Through these steps, the target head model can be reconstructed using shape features extracted from two X-ray images and a frontal facial image. Figure 9 shows the example of the fitting result for an actual patient, (a) is the result deformed only by information from X-ray images. Figure 9 (b) is the last result of detailed fitting using both of X-ray images and a facial image.



(a) Width fitting (b) Area division (c) Vector interpolation

Figure 8. Model fitting process



(a) Rough fitting (b) Detailed fitting

Figure 9. Face reconstruction results

5. Facial Surgery Simulation System

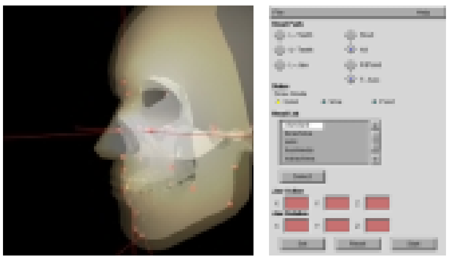


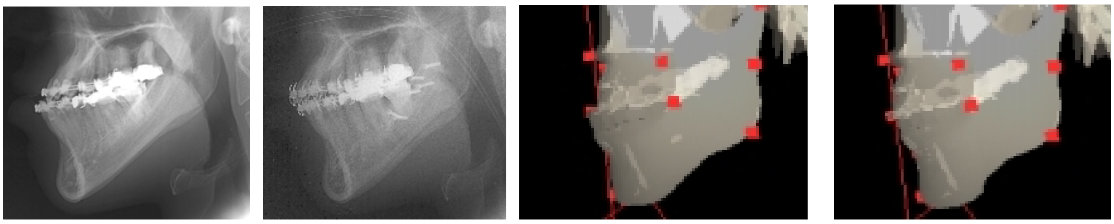
Figure 10. Simulation System

Figure 10 shows the overview of our simulation system. Using the control panel, we can set the values of parameters easily and interactively. These parameters are the stiffness of facial muscles, and jaw action parameters. For the simulation of orthognathic surgery, the parameters for the jaw treatment are especially essential, i.e. the backward movement and the rotation angle of the jaw to bring it into a desired position. This system takes some surgical procedures into account, such as cutting and shifting of the bone, and changes of facial morphology caused by them are automatically computed and demonstrated in the model view window. Our system enables surgeons to make plans for the surgery in advance, and to indicate the postoperative 3D facial images clearly.

6. EXPERIMENTAL RESULTS

6.1 Surgery Simulation

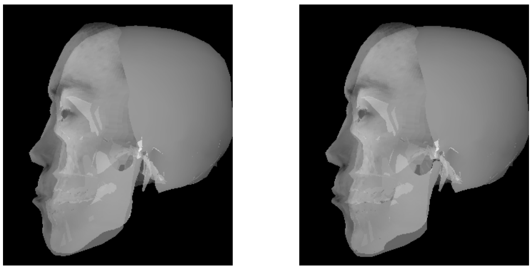
The changes of facial morphology following orthognathic surgery were simulated for three patients with mandibular prognathism. In each case, we input surgical parameters such as the backward distance of the lower jaw, rotation angle around each axis, and so on. The values of surgical parameters are determined by the results of surgical planning of dentists. Figure 11 are the x-ray images of the actual surgery result, compared to the predicted results. Figure 12 illustrates the predicted 3D facial shape after surgery. Figure 13 shows the simulation results which are predicted for other patients. In these figures, predicted facial images are overlapped with the actual results of surgery.



Before surgery After surgery Before surgery After surgery

(Actual X-ray images) (Simulated results)

Figure 11. Simulation result (Skull)



Before surgery After surgery

Figure 12. Simulation result (Facial morphology)

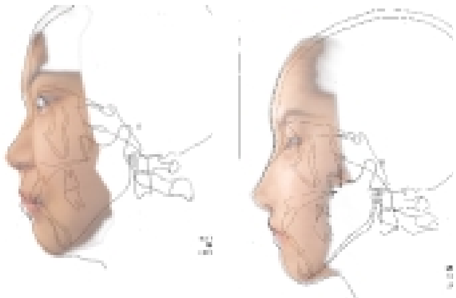


Figure 13. Simulation results compared to actual surgery results

6.2 Facial Dynamics Simulation

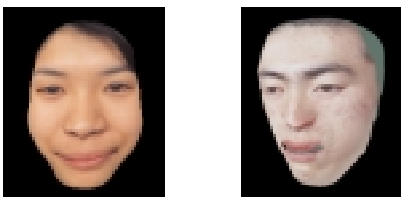


Figure 14. Facial expressions after surgery

We simulated not only static facial morphology, but also facial dynamics after surgery. Figure 14 shows facial expressions generated on faces after surgery. These results indicate that our face model is able to compare facial dynamics between before and after surgery.

7. CONCLUSION AND FUTURE WORK

We proposed a head modeling method from normalized X-ray and facial images and a facial surgery simulation system as an application. Without using 3D-CT or MRI, our method is capable of reconstructing 3D head shape briefly from extracted facial features. In the experiment, we predicted the 3D facial shape after orthognathic surgery for patients with mandibular prognathism, using the actual data set of patients. By comparing the simulation results and the actual postoperative facial images, the proposed method can be proved to be practically useful.
For future works, we should investigate how to fit the parameters of skin and muscles' stiffness for each patient in detail to improve the accuracy of modeling and simulation results. In the near future, we attempt to evaluate the difference between predicted results and actual facial shapes quantitatively using 3D-CT or MRI data of patients' head, in order to make the system more profitable for actual treatment process.

REFERENCES

[1] D.Terzopoulos and K.Waters, "Analysis And Synthesis of Facial Image Sequences Using Physical and Anatomical Models," IEEE Trans. on PAMI, Vol.15, No.6, pp.569-579, June 1993.
[2] Y.Aoki, S.Hashimoto, "Physical Facial Model based on 3D-CT Data for Facial Image Analysis and Synthesis," Third IEEE International Conference on Automatic Face and Gesture Recognition, pp.448-453, 1998.
[3] Y.Aoki, S.Hashimoto, "Physical Modeling of Face Using Spring Frame based on Anatomical data," IEICE, pp.339-354, 1997.
[4] Y.Lee and D.Terzopoulos et al, "Realistic Modeling for Facial Animation," SIGGRAPH 95 Proceedings, pp.55-62, ACM SIGGRAPH, 1995.
[5] R.M.Koch et al, "Simulating Facial Surgery Using Finite Element Models," SIGGRAPH 96 Proceedings, pp.421-428, ACM SIGGRAPH, 1996.
[6] H.Mita, T.Konno, "A Facial Paralysis Simulator for Surgery Planning," Journal of Japan society for Computer Aided Surgery, Vol.4, No.1, pp.1-5, June 1996.
[7] K.Waters, "A Physical Model of Facial Tissue and Muscle Articulation Derived from Computer Tomography Data," Proceeding of the Second Conference Visualization in Biomedical Computing, Chapel Hill, N.Carolina, SPIE, Vol.1808, pp.574-583, 1992.
[8] W.Lee, P.Kalra, N.M.Thalmann, "Model Based Face Reconstruction for Animation," Proceeding of the 4th International Conference on Multi-Media Modeling, pp.323-338, 1997.
[9] V.Blanz, V and T. Vetter, "A Morphable Model for the Synthesis of 3D Faces," SIGGRAPH99 Proceedings, pp.187-194, ACM SIGGRAPH'99, 1999.
[10] P.Ekman, W.V.Friesen, "Facial Action Coding System," Consulting Psychologist PressInc, San Francisco, CA 1978.
[11] K.Aizawa, H.Harashima, and T.Saito, "Model-based analysis synthesis image coding system for a person's face," Signal Processing: Image Commun., Vol.1, No.2, pp.139-152, 1989.
[12] S.Hashimoto, Y.Sato and H.Oda, "Modeification of Facial Expression Using Spring Frame Model," Proceedings of IASTED, pp.9-15, 1989.
[13] M.Gotla, Z.Huang, “Minimalist Approach to Facial Reconstruction,” Proceedings of the 5th Int’l Conference on Multi Media Modeling (MMM’99), pp.377-387, Ottawa, 1999.
[14] T.Yokoyama, et al, “Extracting Contours and Features from Frontal Face Images,” The Journal of the Institute of Image Information and Television Engineers, Vol.53, No.11, pp.1605-1614, 1999.