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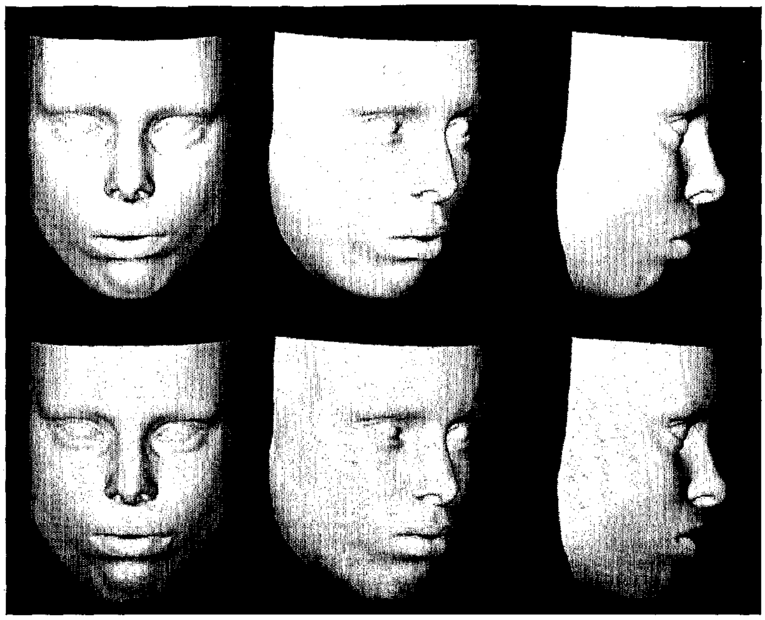
(54) **Title:** METHOD AND SYSTEM FOR PRE-OPERATIVE PREDICTION



(57) **Abstract:** The present invention is related to a method for pre-operatively obtaining a prediction of a post-operative image of at least part of a body, comprising the steps of : determining a 3D pre-operative description of at least part of a body, acquiring a pre-operative 2D photograph of said at least part of the body from any viewing position, matching the 3D pre-operative description with the pre-operative 2D photograph, determining a deformation field for deforming the 3D pre-operative description, and deriving by means of the deformation field and the pre-operative 2D photograph a predicted post-operative image of a 3D post-operative description of the at least part of the body.

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# METHOD AND SYSTEM FOR PRE-OPERATIVE PREDICTION

## Field of the invention

[0001] The present invention relates to a method for the pre-operative prediction of a body or a part of a body, e.g. the face, after surgery. The invention also relates to a planning system wherein the method can be applied.

## State of the art

[0002] In maxillofacial and plastic surgery or dermosurgery parts of the body, such as the skull, dentition, soft tissues or skin patches, are surgically remodelled or restored. An example is orthognatic surgery, in which the relation of the jawbones is adjusted. Another example is breast augmentation, in which the breasts are enlarged using breasts implants.

[0003] Generating realistic images (e.g. of faces) has been a central goal in three-dimensional (3D) shape acquisition, animation and visualisation.

### 3D acquisition

[0004] Several methods exist to acquire a 3D geometric description of (a part of) the body. Well-known are the medical imaging modalities, such as CT and MRI, and 3D photographic systems. The latter can be subdivided into two categories, i.e. those using active methods, which project a specific pattern on the body, and those using passive methods, which acquire a 3D geometric description of the body from one or more images and illumination conditions, with or without the use of a priori geometric knowledge. Simultaneously with the 3D geometric description, 3D photographic systems deliver the texture of the body, which is used to render the 3D surface.

Animation

[0005] Several methods exist to animate a 3D body shape. Motion simulation can be based on heuristic rules, physics-based knowledge, or it can be image-derived (e.g., building a statistical deformation model based on a set of images from different persons and/or expressions). The result can be natural or artificial. For example, the facial motion of one person can be used to drive the facial motion of another person.

Visualisation

[0006] 3D visualisation or rendering uses a texture map and a reflectance model of the (part of the) body.

[0007] Texture mapping refers to a computer graphics technique wherein a texture image (or texture map) is applied to a polygonal mesh or some other surface representation by coupling the texture image (or texture map) (with associated colour/gray value) to the 3D surface. The result is that (some portion of) the texture image is mapped onto the surface when the surface is rendered.

[0008] Texture is derived from one or more 2D or 3D photographs of the body. When using a 3D photographic system, a texture map is typically delivered simultaneously with the 3D shape description.

When using 2D photographs, a method to match or register these 2D photographs with the 3D surface description is needed. Matching can be done based on a set of corresponding points, or on a metric (e.g., mutual information) that expresses the correspondence between 2D-image-derived features and 3D-shape-based properties.

[0009] The model of body reflectance can be based on skin or skin-like diffuse and specular (mirror-like reflection) properties.

[0010] 2D visualisation has been used to show (a part of) the body under simulated or artificial illumination conditions and for animation by morphing (part of) the body. In these applications, photo-realism is the primary concern.

[0011] The following prior art documents are the closest to the subject-matter of the present invention.

- *'Computer-assisted three-dimensional surgical planning and simulation',J Xia et al., 3D color facial model generation,Int J Oral Maxillofac Surg,29, pp.2-10, 2000,*
- *'Computer-assisted three-dimensional surgical planning and simulation: 3D soft tissue planning and prediction', Xia et al., Int J Oral Maxillofac Surg, 29, pp.250-258, 2000,*
- *'Three-dimensional virtual reality surgical planning and simulation workbench for orthognathic surgery', Xia et al., Int J Adult Orthod Orthognath Surg, 15(4), 2000,*
- *'Three-dimensional virtual-reality surgical planning and soft-tissue prediction for orthognatic surgery', Xia et al., IEEE Information Technology in biomedicine 5(2), pp. 97-107, 2001,*
- *'Fast Texture mapping of photographs on a 3D facial model', Iwakiri et al., Proc Image and Vision Computing New Zealand 2003, Nov. 2003, Palmerston North, New Zealand, pp.390-395.*

[0012] The methods of Xia et al. and of Iwakiri et al. use a set of photographs comprising a frontal (0° view), right (90° view) and left (270° view) photograph of the patient, which are projected as a texture map onto the 3D head mesh obtained from CT for 3D visualisation.

## Aims of the invention

[0013] The present invention aims to provide a device and method for pre-operatively simulating or predicting an accurate image of the patient's appearance after surgery, in particular maxillofacial or plastic surgery. In another aspect the invention aims to provide a planning system wherein the method can be applied.

## Summary of the invention

[0014] The present invention relates to a method for pre-operatively obtaining a prediction of a post-operative image of at least part of a body, comprising the steps of :

- determining a 3D pre-operative description of at least part of a body,
- acquiring a pre-operative 2D photograph of the at least part of the body from any viewing position,
- matching the 3D pre-operative description with the pre-operative 2D photograph,
- determining a deformation field for deforming the 3D pre-operative description, typically with a 3D planning system, and
- deriving by means of the deformation field and the pre-operative 2D photograph a predicted post-operative image of a 3D post-operative description of the at least part of the body.

[0015] In a preferred embodiment the predicted post-operative image is a 2D photograph obtained by deforming the pre-operative 2D photograph using said deformation field.

[0016] In another preferred embodiment the predicted post-operative image is a 3D image. In this case a plurality of pre-operative 2D photographs is advantageously acquired and subsequently used in the later method steps.

[0017] The method advantageously further comprises a step of generating from the 3D pre-operative description a 3D pre-operative surface mesh of at least the contours of the at least part of the body. The step of deriving the predicted image comprises deriving from the 3D pre-operative surface mesh a prediction of the 3D post-operative surface mesh of at least the contours of the at least part of the body. The prediction of the contours is then used in the determination of the deformation field.

[0018] In another embodiment the 3D pre-operative description is obtained using a 3D image acquisition system. Such 3D image acquisition system can be a Computerised Tomography system, a Magnetic Resonance Imaging system or a 3D photographic system.

[0019] The step of matching is preferably performed by means of a set of corresponding points on said 3D pre-operative description and said 2D pre-operative photograph. Alternatively said step of matching is performed by means a metric expressing the correspondence between features derived from the pre-operative 2D photograph and properties based on the 3D pre-operative description.

[0020] In a more specific embodiment the method further comprises the step of taking a picture of a calibration object. Said picture of the calibration object can then be used for calibrating the camera with which the pre-operative 2D photograph are acquired.

[0021] After the matching step advantageously a step is performed of creating from the matched pre-operative 2D photographs a texture map for 3D visualisation.

[0022] The 3D pre-operative description comprises typically a soft tissue description of the at least part of the body. Advantageously it also comprises information about the internal structure of the at least part of the body.

[0023] In another aspect the invention also relates to a surgical planning system for pre-operatively showing a predicted post-operative image of at least part of a body, comprising

- means for determining a 3D pre-operative description of at least part of a body,
- means for matching the 3D pre-operative description with a 2D pre-operative photograph of the at least part of the body,
- calculation means for determining a deformation field to deform the 3D pre-operative description and for deriving a predicted post-operative image of a 3D post-operative description of the at least part of the body,
- display means for showing the predicted post-operative image.

[0024] In a specific embodiment the predicted post-operative image is a 3D image. Alternatively the predicted post-operative image is a predicted post-operative 2D photograph obtainable by deforming the pre-operative 2D photograph using the deformation field.

## Short description of the drawings

[0025] Fig. 1a represents a 3D pre-operative surface mesh, projected onto the 2D pre-operative photographs after registration. Fig.1b and Fig.1c show 2D pre-operative and post-operative photographs, respectively. Fig.1d represents two views of the rendered surface mesh, using a texture map obtained from the set of 2D photographs.

[0026] Fig. 2a represents a 3D pre-operative surface mesh, projected onto the 2D pre-operative photographs after registration. Fig.2b and Fig.2c show 2D pre-operative and post-operative photographs, respectively. Fig.2d represents two views of the rendered surface mesh, using a texture map obtained from the set of 2D photographs.

[0027] Fig. 3a represents a 3D surface mesh, obtained with a 3D photographic system, projected onto the 2D photographs after registration. Fig.3b shows 2D photographs. Fig.3c offers six views of the rendered surface mesh using a texture map obtained from the set of 2D photographs.

[0028] Fig. 4 represents a calibration object.

[0029] Fig. 5 represents on the left a set of points specified manually onto the 3D rendered untextured surface, obtained from the 3D surface mesh and on the right a set of (bright) points specified manually onto the 2D photograph, together with the above set of (dark) points obtained by matching the 3D surface with the 2D photograph.

[0030] Fig. 6 represents an iterative improvement of the accuracy by using additional corresponding points on the 2D photograph and the projected surface mesh.

[0031] Fig. 7 gives a schematic representation of the 3D image space I, the 3D camera space C and the 2D photographic image.

[0032] Fig. 8 represents a spherical texture map assembled from the photographs in Fig. 3b.

[0033] Fig. 9 represents from left to right the initial pre-operative skull. The skull is cut into parts that can be repositioned.

[0034] Fig. 10 represents on the top row the pre-operative facial skin surface and on the bottom row the predicted post-operative skin surface.

[0035] Fig. 11 illustrates the planning system accuracy. Above: bone displacement field (up to 13.7 mm). Middle: the rendered surfaces correspond to positions on the face where the difference between simulated (pre-operative) and real (post-operative) surface are less than 2 mm and 1 mm, respectively. Below histogram (left) and cumulative histogram (right) of these differences.

[0036] Fig. 12 represents snapshots of the 3D planning system at work, with facility for soft tissue prediction. The face is shown as a 3D rendered texture surface (pre-operative state). Snapshots of the 3D planning system at work, with facility for soft tissue prediction. The face is shown as a 3D rendered textured surface (simulated post-operative state).

[0037] Fig. 13 represents a cylindrical texture map assembled from the photographs in Fig.2b.

[0038] Fig. 14 represents the deformation field (short lines) projected onto the 2D image.

[0039] Fig. 15 represents the displacement field (short lines) and boundary of the dilated region (outer contour). Outside this area, the displacements are zero and the image is not deformed.

## Detailed description of the invention

[0040] The present invention differs from the prior art in two fundamental aspects. Firstly, in the approach according to the present invention one or more 2D photographs taken from any viewing position can be used. A viewing position is to be considered as a vector having a direction as well as a magnitude, i.e. a viewing position consists of a viewing direction and a camera distance. The number of 2D photographs is thus arbitrary. Secondly, the visualisation is not restricted to 3D visualisation, for which the 2D photographs are used as texture maps, but a single arbitrary pre-operative 2D photograph can be deformed into a simulated post-operative 2D photograph using a physics-based reliable, personalised and accurately predicting 3D deformation field.

While 3D visualisation using texture mapping lacks photo-realism (e.g. unnatural texture blending and hair modelling artefacts (particularly when using medical imaging, such as CT for 3D image acquisition), the simulated post-operative 2D photograph has intrinsically the same photo-realism as the original pre-operative photograph.

[0041] The ability to show the patient's appearance can be integrated into a system for 3D pre-operative planning. By 'planning system' is meant a software environment that allows a physician to plan or simulate the procedure of an intervention. It can for example be used to predict the outcome of that intervention, to try out different procedures, to optimise the procedure, to prepare it and to improve the communication between the medical staff and with the patient.

[0042] Real time 3D visualisation using texture mapping offers an added value to the surgeon while using the 3D planning system, e.g. when adjusting or repositioning bony structures or an implant. Accuracy and integration in the planning procedure are of primary importance, and photo-realism is of minor importance. Visualisation is possible from any viewing direction.

[0043] The 2D geometrically deformed photographs on the other hand offer both high accuracy and high photo-realism and are for example an excellent means to discuss the expected outcome of a surgical procedure with the patient. Although visualisation is restricted to the viewing directions of the original 2D photographs, the number as well as the viewing directions can be arbitrarily chosen.

[0044] In an initial step of the method according to the invention a 3D pre-operative image is acquired of (a part of) a patient's body. A 3D image acquisition system is preferably used thereto, such as CT (Computerised Tomography), MRI (Magnetic Resonance Imaging) or any other 3D scanning or photographic system. 3D medical imaging modalities, such as CT or MRI, offer geometric information of the body contour (further also referred to as the 'soft tissue') and internal structures, such as the bony structures. Based on the volumetric data, the 3D contour of the skin and other tissues, such as bone, are segmented. In the case of skin and bone, segmentation can for example be performed by simple thresholding. Instead of a 3D medical imaging modality, any other 3D scanning device can be used to obtain the outer body contour, such as a 3D photographic system. 3D photographic systems can be subdivided into two categories, i.e. those using active methods, which project a specific pattern on the body, and those using passive methods, which acquire a 3D geometric description of the body from one or more images and illumination conditions, with or without the use of a priori geometric knowledge. In '*Modeling and animating realistic faces from images*' (*Pighin et al., Int J Comp Vision 50(2), pp.143-169, 2002*) for example, a 3D generic face model is interactively fitted to a set of images to acquire the 3D shape.

[0045] Next a set of (one or more) 2D photographs of (a part of) the body from any viewing direction and camera distance (i.e. any viewing position as previously defined) using any camera is acquired. As illustrated in Figs. 1b, 2b and 3b, one or more 2D pictures are taken from arbitrarily chosen directions. To improve the accuracy of the registration method as described below, it is recommended to take a picture of a calibration object (Fig. 4) to calculate the internal parameters of the camera and to freeze these settings during the remainder of the photo session (see below).

[0046] The 3D data are used to generate a 3D surface mesh of the body contour (the 'soft tissue') and, if needed by the planning system, of other tissues such as bone. Surface meshes such as the triangular meshes shown in Figs. 1a, 2a and 3a, can for example be created using the marching cubes algorithm.

[0047] A registration method is then applied to match or register the 3D pre-operative surface description with the 2D photographs. One way to align or register the 3D surface with a 2D photograph is shown in Fig.5, where a set of corresponding points on the 3D surface and the 2D photograph, respectively, is used. The problem then is how to transfer a point from the 3D image space $I$ to the related camera space $C$ and further to the corresponding 2D photographic image. It is assumed that the camera can be modelled as a perspective pinhole camera with its optical centre located at $c$ (see Fig. 7). The geometric relation between $I$ and $C$ can then be expressed by a rotation $R$ and a translation $l$. Once the coordinates of a point $p(x, y, z)$ in $C$ are known, its projection $(x_p, y_p, f)$ in the plane $z = f$ can easily be calculated using the following equations (see Fig. 7):

$$\frac{x}{x_p} = \frac{z}{f} \qquad \frac{y}{y_p} = \frac{z}{f} \qquad \text{(eq.1)}$$

This projection can be written in matrix form as follows :

$$\begin{bmatrix} x_p \\ y_p \\ 1 \end{bmatrix} \cong \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \qquad \text{(eq.2)}$$

Next, a photographic image with coordinates $(u, v)$ is acquired from the projection image in the plane $z = f$. This readout process is subject to a scaling, shear and translation, which can be represented as a 3 × 3 matrix. Hence,

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \cong \begin{bmatrix} s_x & k_x & u_0 \\ k_y & s_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_p \\ y_p \\ 1 \end{bmatrix} \qquad \text{(eq.3)}$$

Combining (Eq.2) and (Eq.3) yields

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \cong \begin{bmatrix} s_x & k_x & u_0 \\ k_y & s_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \qquad \text{(eq.4)}$$

For technical reasons related to the camera readout mechanism, $k_y$ is usually 0. Multiplying the matrices in Eq. (4) and substituting $s_x \cdot f$, $s_y \cdot f$ and $k_x \cdot f$ by $f_x$, $f_y$ and $\kappa_x$, respectively, yields :

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \cong \begin{bmatrix} f_x & \kappa_x & u_0 & 0 \\ 0 & f_y & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \qquad \text{(eq.5)}$$

The transformation matrix in (Eq.5) contains five parameters. When these parameters are known, the camera is said to be calibrated internally. The camera is calibrated externally if the six degrees of freedom of $I$ and $R$ are known. Together, the whole calibration process thus requires eleven parameters to be defined. This can be done by indicating a set of corresponding points on respectively the 3D surface and the 2D photograph (Fig. 5). Each such point yields two equations. This means that at least six points are needed to calculate the value of the eleven parameters. In practice, more reference points are recommended in order to improve the accuracy of the solution.

[0048] The internal calibration parameters are very sensitive to small errors on the position of the corresponding reference points. As already mentioned, it is therefore recommended to take first a picture of a separate calibration object with accurately known geometry and texture (Fig. 4), to calculate the internal parameters of the camera, and to freeze these settings during the remainder of the photo session. The corresponding reference points on the acquired 3D image and 2D photographic image of (part of) the body (Fig. 5) are subsequently used for the external calibration.

The accuracy of the registration can iteratively be improved by adding corresponding points on the 2D photograph and the projected surface mesh (Fig. 6).

Instead of using a set of corresponding points, registration of the 3D surface with a 2D photograph can also be performed for example based on the optimisation of an objective function that expresses the correspondence between 2D-image-derived features and 3D-shape-based properties (e.g., mutual information).

[0049] In a further step a 2D texture map is created from the registered 2D photographs. The surface mesh and corresponding texture are used for 3D visualisation. The texture map is then mapped onto the 3D body surface. View-dependent (using a single texture map for fast displaying, e.g. a virtual sphere enclosing the 3D body contour) and view-independent texture mapping (Fig.8) assume a known relationship between the 3D surface coordinates and the 2D photographic coordinates, as well as a method to calculate the texture values from the colours or gray values in the available photographs.

Once the 2D photographs and 3D surface are matched, the mapping between the 3D surface coordinates and the 2D coordinates in each photograph is known. Each 3D mesh point corresponds to a point in each 2D photograph and its texture value is nonzero if the 3D mesh point is visible in and front facing at least one of the 2D photographs. Hence, for each 2D photograph, a corresponding "visible mesh" is generated by removing the vertices that are invisible from the camera position, together with the triangles they belong to.

The texture value can for example be calculated as a normalised weighted combination of the corresponding colour or gray values in the contributing photographs as proposed in the above-mentioned papers by Pighin or by Iwakiri. This weight function should provide a smooth and seamless transition between the photographic patches. For example, in Figs. 1d, 2d and 3c the weight function $(\theta-\pi/2)^2$ has been used, with $\theta$ the angle between the surface normal and the line from the surface point to the camera position of the photograph.

[0050] A 3D patient-specific planning system (e.g., for maxillofacial surgery, breast augmentation, nose correction, etc.), including a soft tissue prediction, is used to simulate the post-operative shape. The soft tissue prediction is used to deform the pre-operative surface mesh of the soft tissue with associated texture map into a predicted post-operative soft tissue mesh with associated remapped texture. The post-operative soft-tissue mesh and corresponding texture map is used for 3D visualisation of the soft tissue.

[0051] Several methods exist to animate a 3D body shape. Motion simulation can be based on heuristic rules, physics-based knowledge, or it can be image-derived (e.g., building a statistical deformation model based on a set of images from different expressions or a linear combination of a set of textured face meshes each corresponding to a facial expression, such as joy, anger, sadness). The result can be natural or artificial (e.g., the facial motion of one person can be used to drive the facial motion of another person).

[0052] The invention makes use of a personalised and accurately predicting 3D deformation field for maxillofacial and plastic surgery. As an example, the next paragraph describes a 3D planning system for maxillofacial surgery, which yields an accurate personalised 3D deformation field of the face.

[0053] Planning a maxillofacial procedure can be subdivided into two separate parts, i.e., the bone-related planning and the soft tissue simulation.

The bone-related planner allows the surgeon to reshape the skull in a 3D environment. Reshaping the skull implies cutting the skull into different parts and repositioning each of the different parts (Fig. 9). Starting from a bone related planning, the new facial shape of the patient can be simulated (Figs. 10). To predict the new facial outlook, a mathematical model is used that is able to accurately simulate the behaviour of the facial tissues. Known models are the finite element model (FEM), the mass-spring model (MSM) and the mass-tensor model (MTM). Together with one of these models, a set of boundary conditions is used, which are generated from the bone-related planning. In '*Very fast soft tissue predictions with mass tensor model for maxillofacial surgery planning systems*' (Mollemans et al., Proc Computer Assisted Radiology and Surgery (CARS), 2005) for example, it is assumed that the soft tissue is attached to the bone in a number of locations and that the soft tissue in these points follows the same motion trajectory as the corresponding attaching skull points. The deformation of the remainder of the soft tissue is found by requiring that the total force in each such soft tissue point should be zero or by integrating a motion equation over time. Fig. 11 shows the accuracy of the simulation.

[0054] Fig. 12 shows a few snapshots of the planning system at work on the same patient as used in Figs 9-11. The soft tissue with associated texture moves in real time and simultaneously with the bone displacements. Fig. 13 shows the associated texture map for this patient.

[0055] In a further step the 3D pre-operative and post-operative surface meshes are projected onto the pre-operative 2D photographs. The vertices of the pre-operative 3D surface meshes that are visible from the camera viewpoint were previously mapped or projected onto the pre-operative 2D photographs (Fig. 1a, 2a, 3a) using the registration parameters and matrices previously obtained. For each of these vertices a displacement vector and corresponding vertex in the post-operative 3D surface mesh is known. These corresponding vertices are also projected onto the pre-operative 2D photographs. Since the pre-operative 3D surface mesh is deformed into a post-operative mesh, some vertices that were previously visible, may become invisible now. These vertices are also removed as well as their associated vertex in the pre-operative mesh.

[0056] The projected deformation field, acquired from the pre-operative and post-operative soft-tissue meshes, is used to geometrically deform the pre-operative 2D photographs and predict the post-operative 2D photographs (Fig. 1c, 2c).

[0057] In computer graphics, pure 2D image processing using a colour/gray value transformation and/or a geometric transformation has been exploited to show (part of) the body under simulated or artificial illumination conditions and for animation by morphing (part of) the body. In these applications, photo-realism is the primary concern. In maxillofacial and plastic surgery, however, the simulated images must accurately predict the post-operative appearance.

[0058] In this invention, a patient-specific 3D deformation model is used to deform the 2D photographs geometrically. From the projected pre-operative and post-operative soft-tissue meshes, the 2D displacement of all the projected mesh vertices in the 2D photograph is known. Hence, the 2D geometric deformation vector is known in a discrete number of points in the 2D photograph (Fig. 14). The displacement in each pixel of the photograph can then be calculated by interpolation between the discrete deformation vectors. Outside the projected mesh, the deformation is in principle zero. However, due to small mismatches between the 2D photograph and the projected pre-operative surface mesh, it may be recommended to slightly extrapolate the deformation field outside the mesh. Mismatches particularly occur if the posture of the (part of) the body is different in the 2D photograph and the 3D surface (e.g. taken in standing and lying position, respectively). Fig. 15 is a typical example. In this case, the contour of an enlarged region can be used as the zero-deformation borderline. Within this region, interpolation of the discrete deformation field can for example be performed using bicubic spline functions.

[0059] The above method can also be used in practice without the steps of determining a deformation field and using the deformation field to deform the one or more pre-operative 2D photographs. The latter step results in a predicted post-operative 2D photograph. However, 3D visualisation using texture mapping lacks photo-realism (e.g. unnatural texture blending and hair modelling artefacts (particularly when using medical imaging, such as CT for 3D image acquisition) and the texture map mostly needs retouching. The simulated post-operative 2D photograph on the other hand, has intrinsically the same photo-realism as the original pre-operative photograph.

## CLAIMS

1. Method for pre-operatively obtaining a prediction of a post-operative image of at least part of a body, comprising the steps of :

- determining a 3D pre-operative description of at least part of a body,
- acquiring a pre-operative 2D photograph of said at least part of said body from any viewing position,
- matching said 3D pre-operative description with said pre-operative 2D photograph,
- determining a deformation field for deforming said 3D pre-operative description, and
- deriving by means of said deformation field and said pre-operative 2D photograph a predicted post-operative image of a 3D post-operative description of said at least part of said body.

2. Method as in claim 1, wherein said predicted post-operative image is a 2D photograph, whereby said 2D photograph is obtained by deforming said pre-operative 2D photograph using said deformation field.

3. Method as in claim 1, wherein said predicted post-operative image is a 3D image.

4. Method as in claim 3, whereby a plurality of pre-operative 2D photographs is acquired.

5. Method as in any of claims 1 to 4, further comprising a step of generating from said 3D pre-operative description a 3D pre-operative surface mesh of at least the contours of said at least part of said body.

6. Method as in claim 5, wherein said step of deriving said predicted image comprises deriving from said 3D pre-operative surface mesh a prediction of the 3D post-operative surface mesh of at least said contours of said at least part of said body.

7. Method as in claim 6, wherein said prediction of said contours is used in the determination of said deformation field.

8. Method as in any of claims 1 to 7, wherein said 3D pre-operative description is obtained using a 3D image acquisition system.

9. Method as in claim 8, wherein said 3D image acquisition system is a Computerised Tomography system, a Magnetic Resonance Imaging system or a 3D photographic system.

10. Method as in any of the previous claims, wherein said step of matching is performed by means of a set of corresponding points on said 3D pre-operative description and said 2D pre-operative photograph.

11. Method as in any of claims 1 to 9, wherein said step of matching is performed by means of a metric expressing the correspondence between features derived from said pre-operative 2D photograph and features derived from said 3D pre-operative description.

12. Method as in any of the previous claims, further comprising the step of taking a picture of a calibration object.

13. Method as in claim 12, wherein said picture of said calibration object is used for calibrating a camera, said camera being used for acquiring said at least one pre-operative 2D photograph.

14. Method as in any of claims 4 to 13, wherein after said step of matching a step is performed of creating from said matched pre-operative 2D photographs a texture map for 3D visualisation.

15. Method as in any of the previous claims, wherein said 3D pre-operative description comprises a soft tissue description of said at least part of said body.

16. Method as in any of the previous claims, wherein said 3D pre-operative description of said at least part of said body comprises information about the internal structure of said at least part of said body.

17. Surgical planning system for pre-operatively showing a predicted post-operative image of at least part of a body, comprising

- means for determining a 3D pre-operative description of at least part of a body,
- means for matching said 3D pre-operative description with a 2D pre-operative photograph of said at least part of said body,
- calculation means for determining a deformation field to deform said 3D pre-operative description and for deriving a predicted post-operative image of a 3D post-operative description of said at least part of said body,
- display means for showing said predicted post-operative image.

18. Surgical planning system as in claim 17, wherein said predicted post-operative image is a predicted post-operative 2D photograph obtainable by deforming said pre-operative 2D photograph using said deformation field.

19. Surgical planning system as in claim 17, wherein said predicted post-operative image is a 3D image.

Fig. 1a

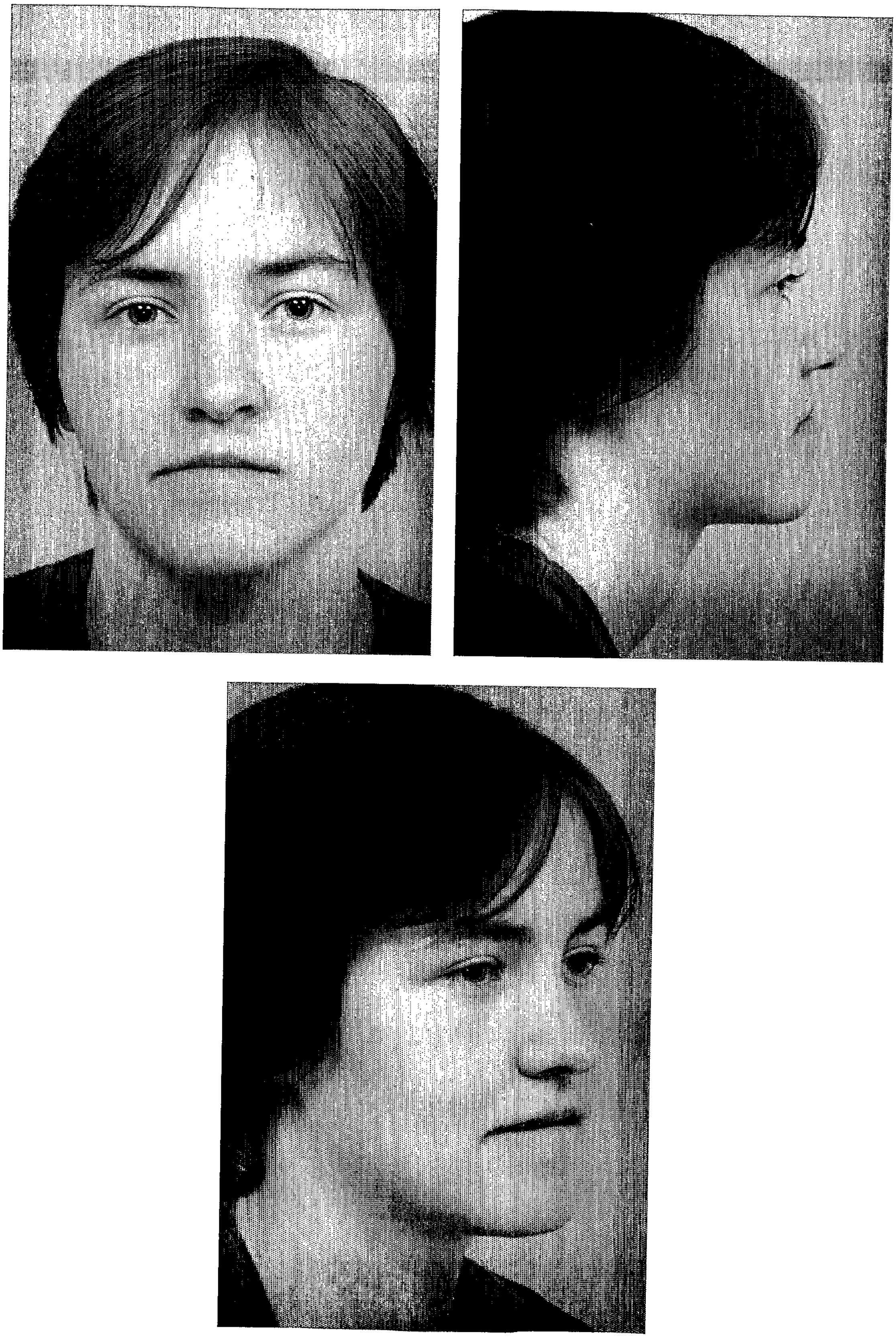


Fig. 1b

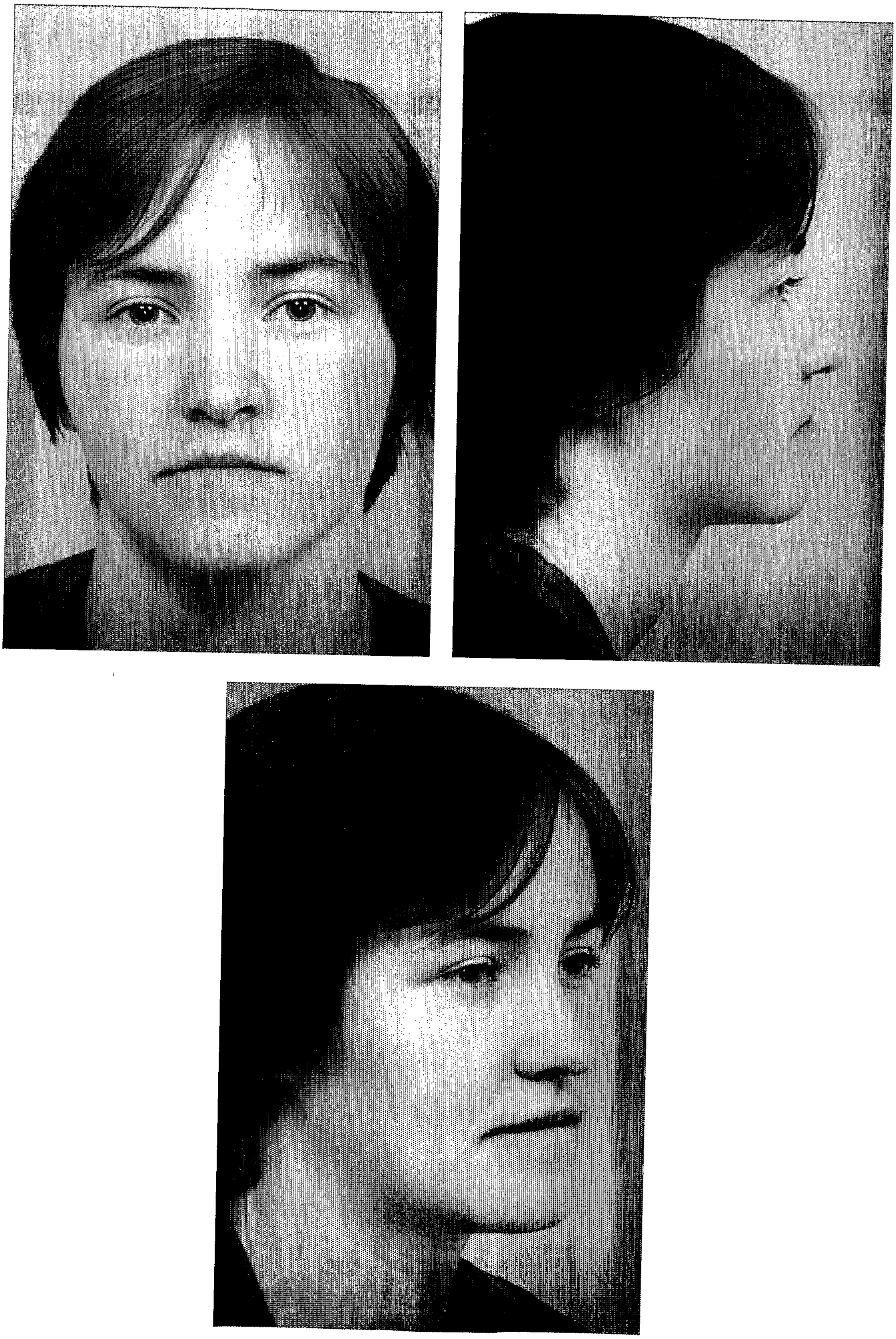


Fig. 1c

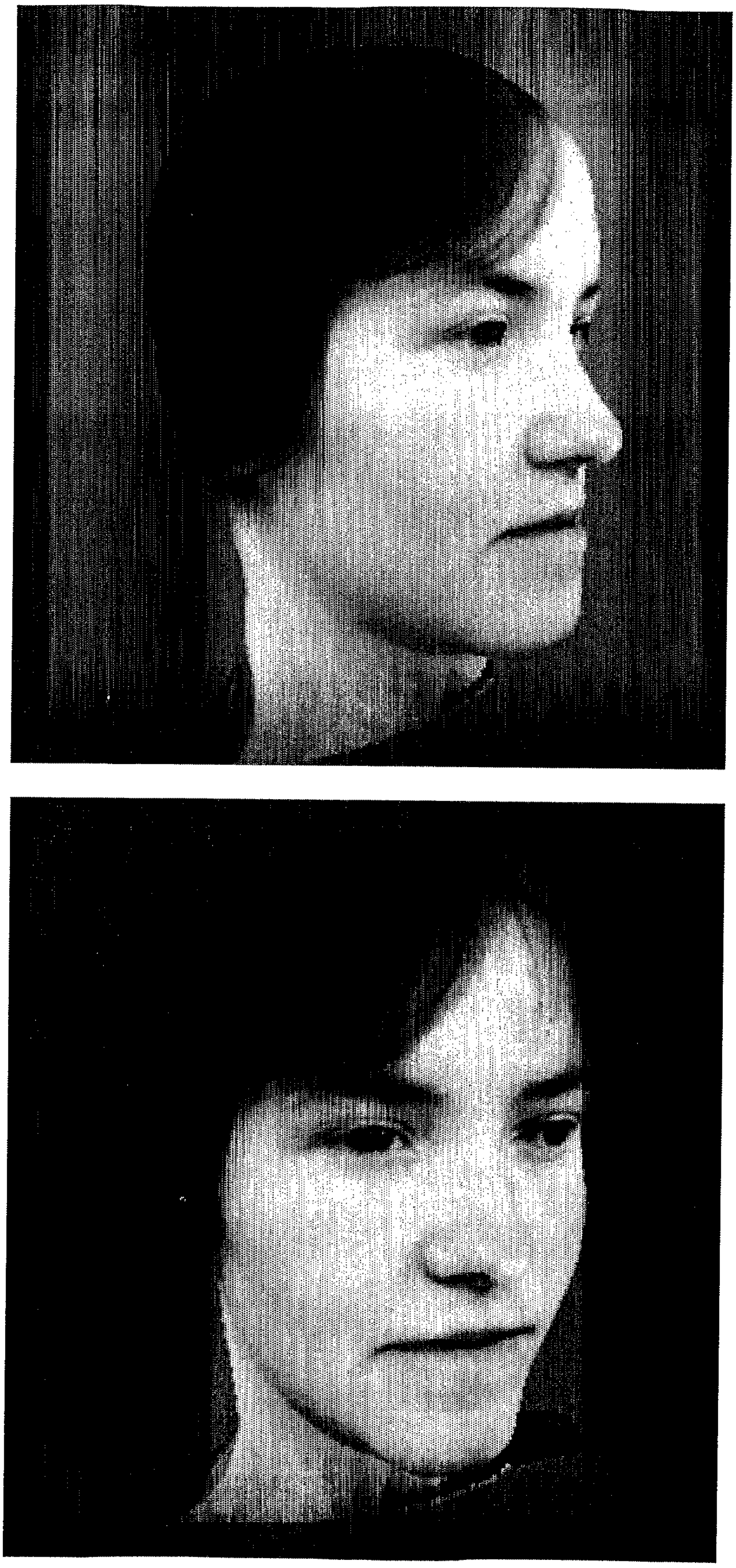


Fig. 1d

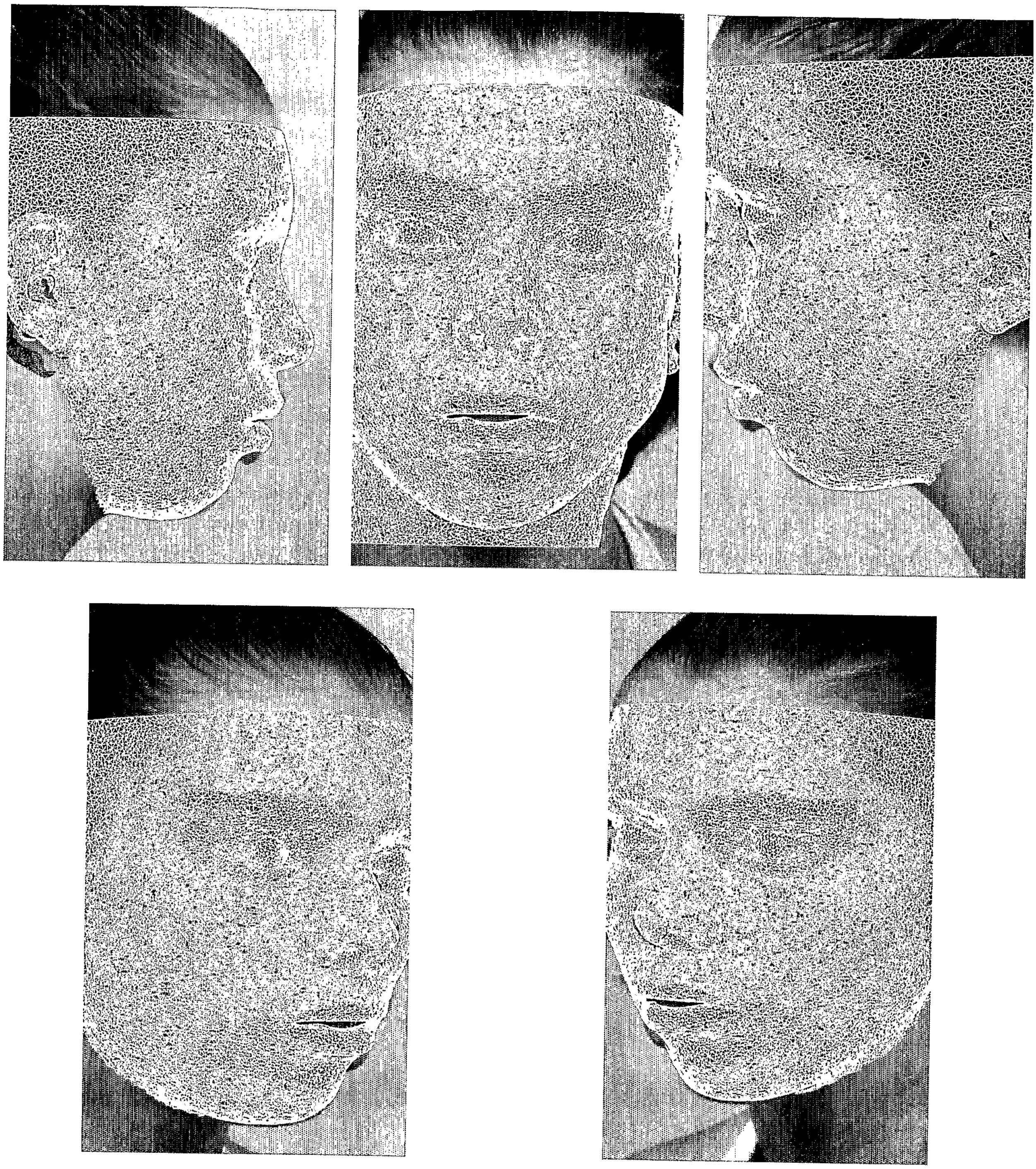


Fig. 2a

Fig. 2b

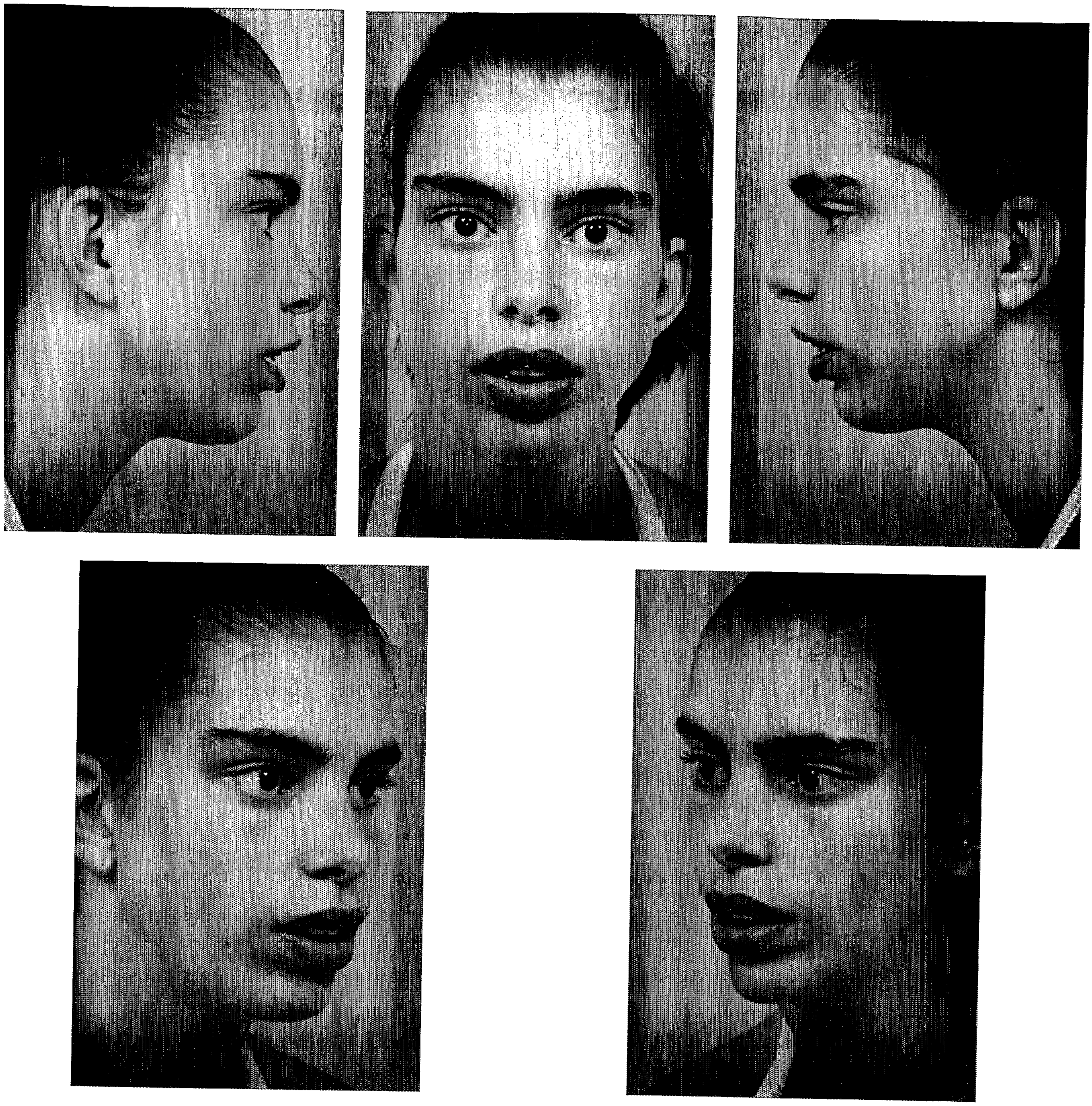


Fig. 2c

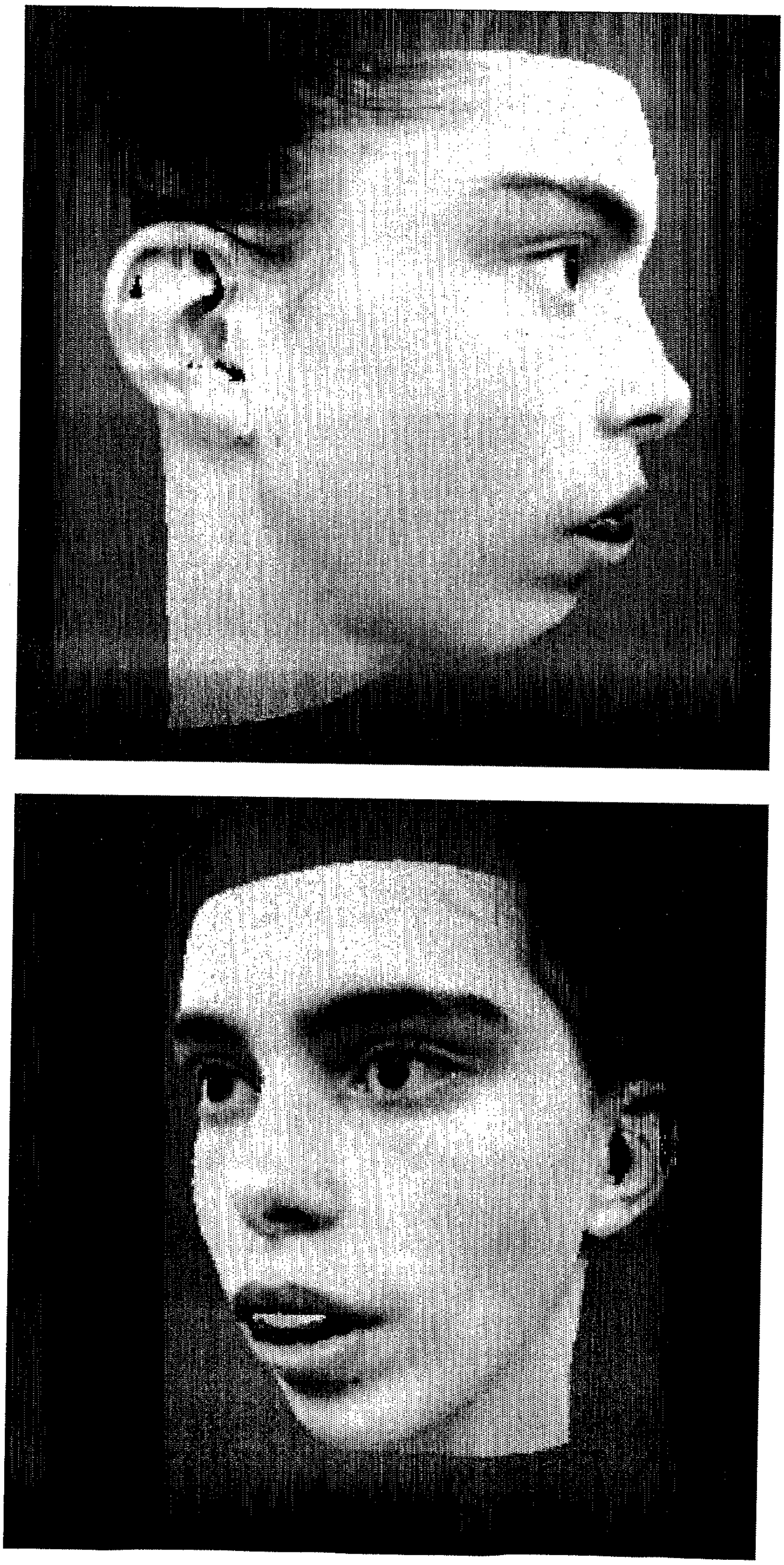


Fig. 2d

Fig. 3a

Fig. 3b

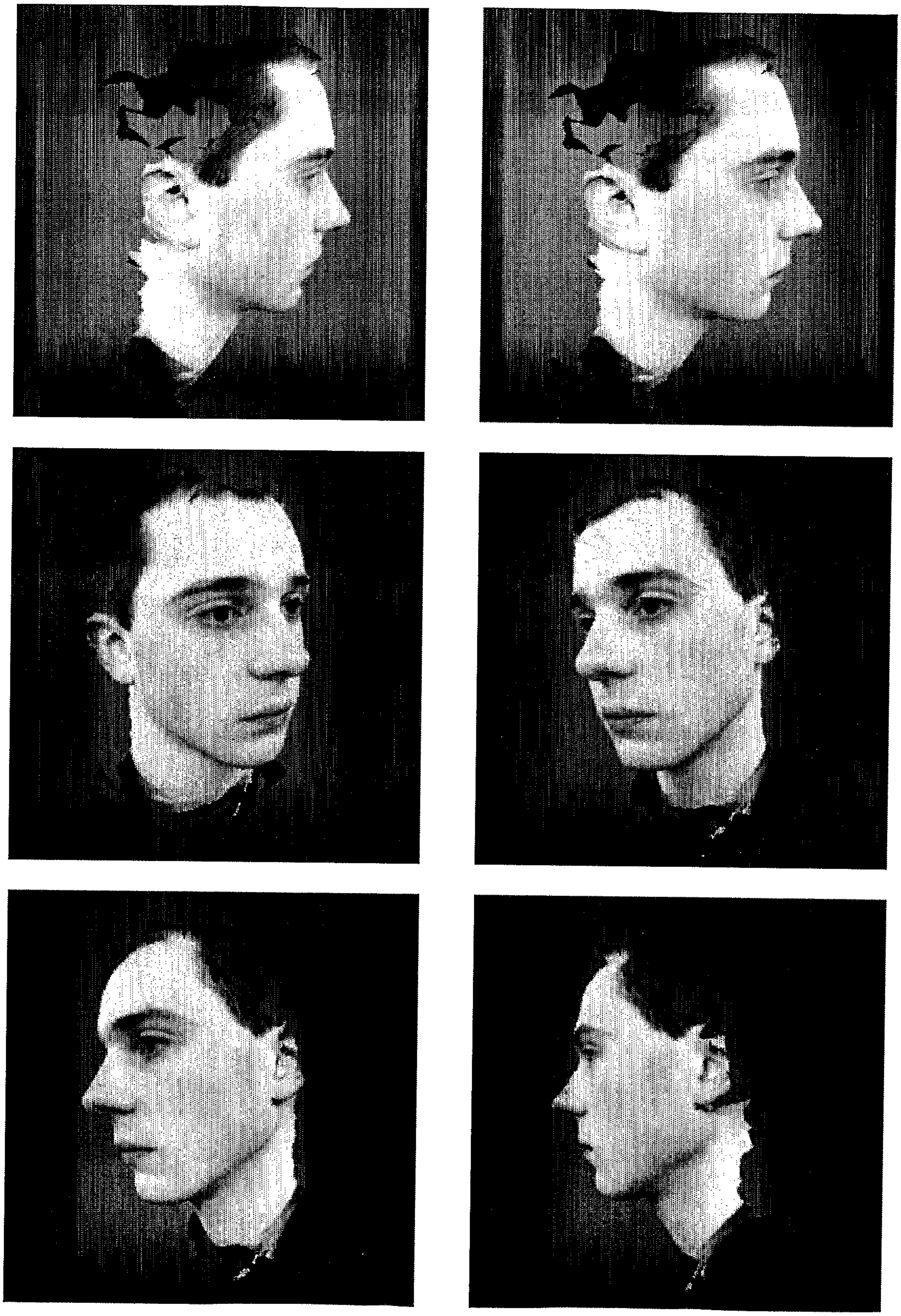


Fig. 3c

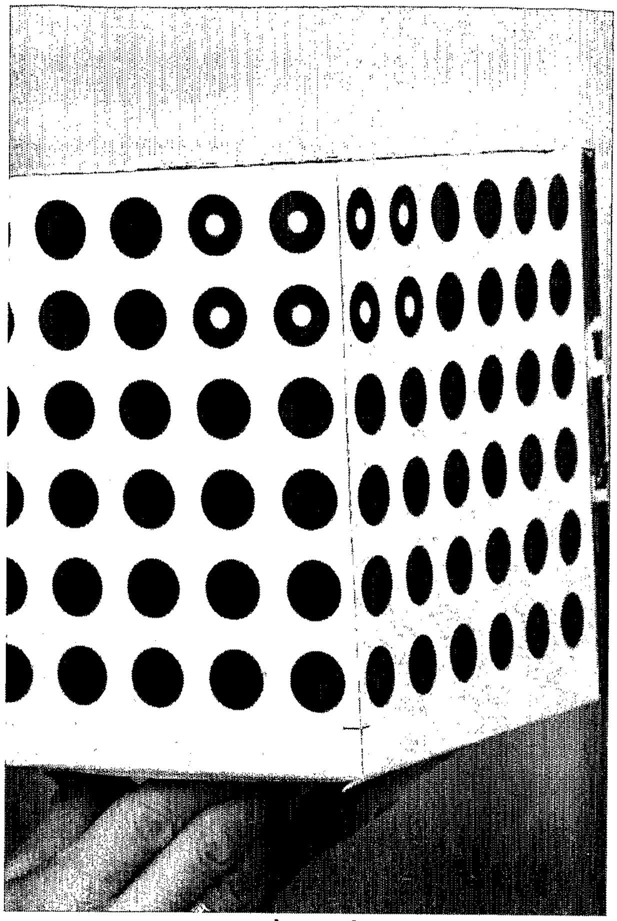


Fig. 4

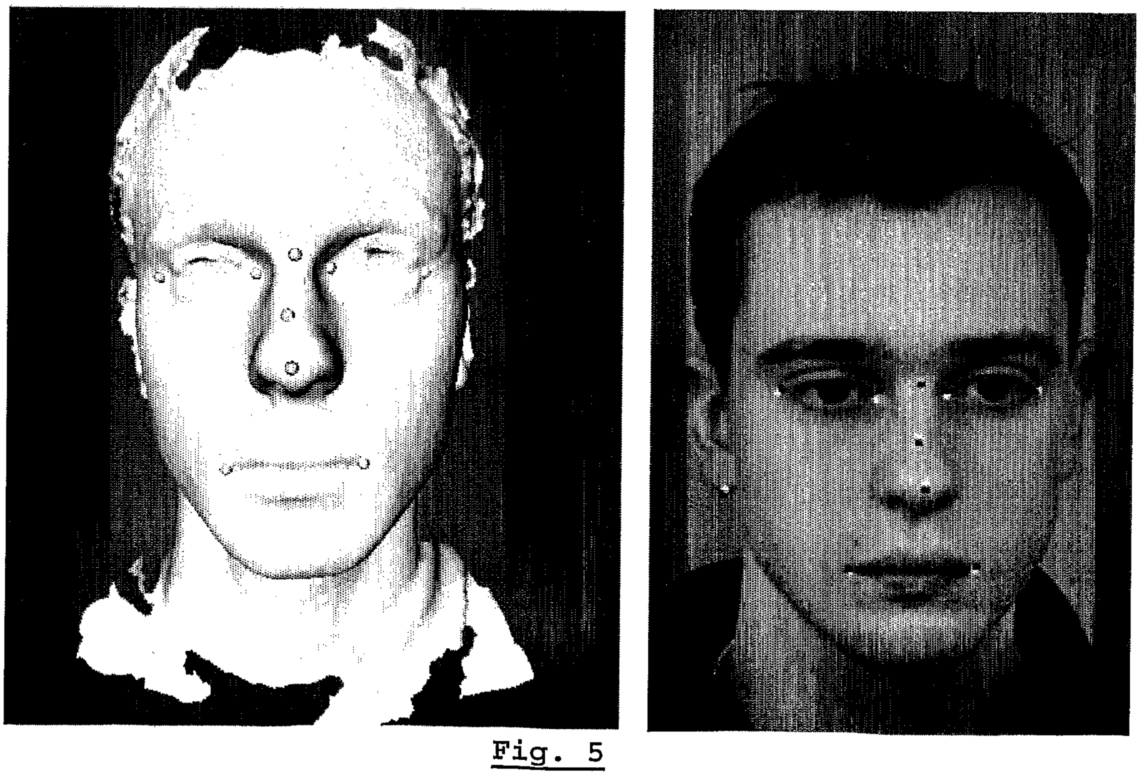


Fig. 5

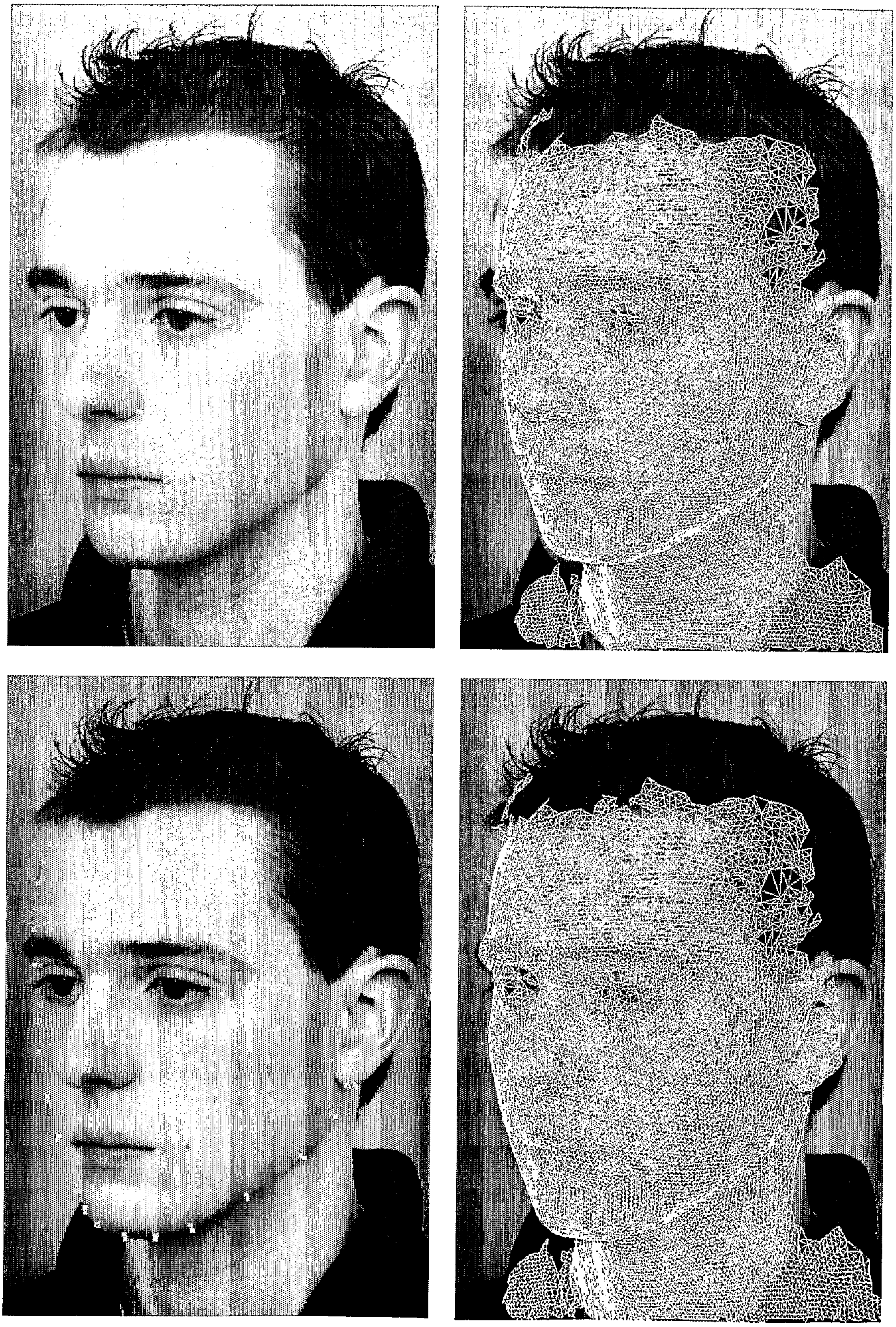


Fig. 6

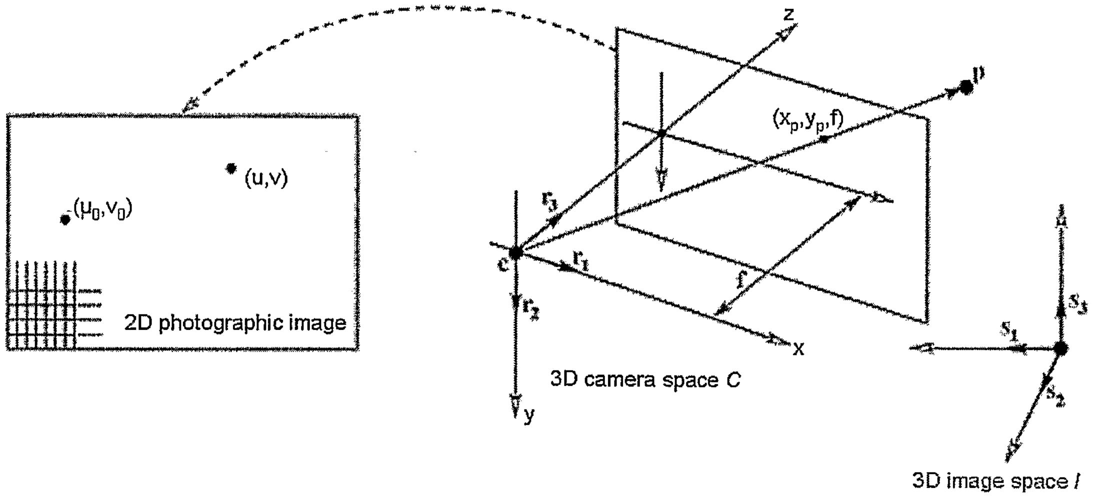

2D photographic image
(u,v)
$(\mu_0,v_0)$
z
p
$(x_p,y_p,f)$
$r_3$
c
$r_1$
$r_2$
f
x
y
3D camera space C
$s_3$
$s_1$
$s_2$
3D image space I

Fig.7

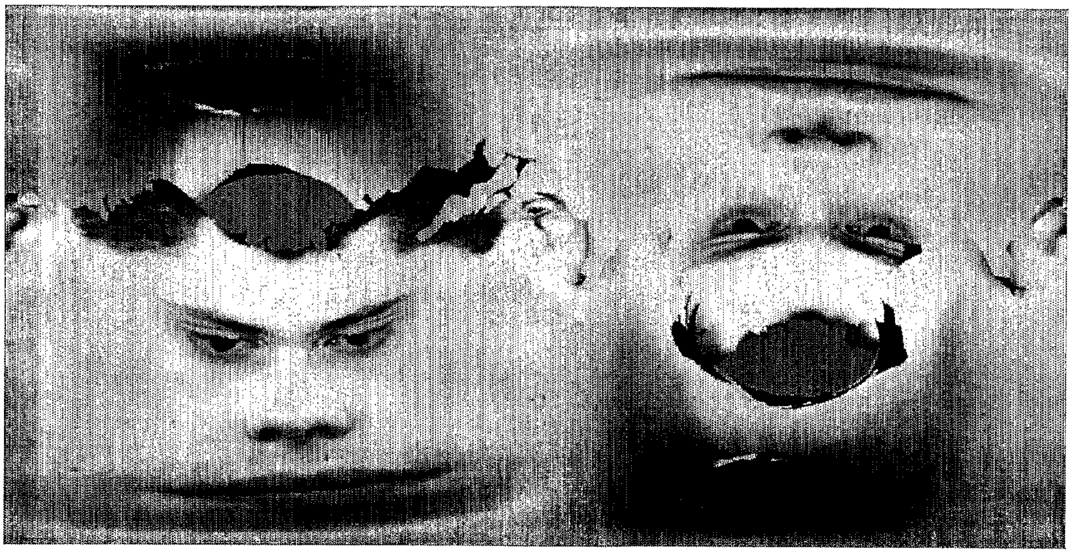


Fig. 8

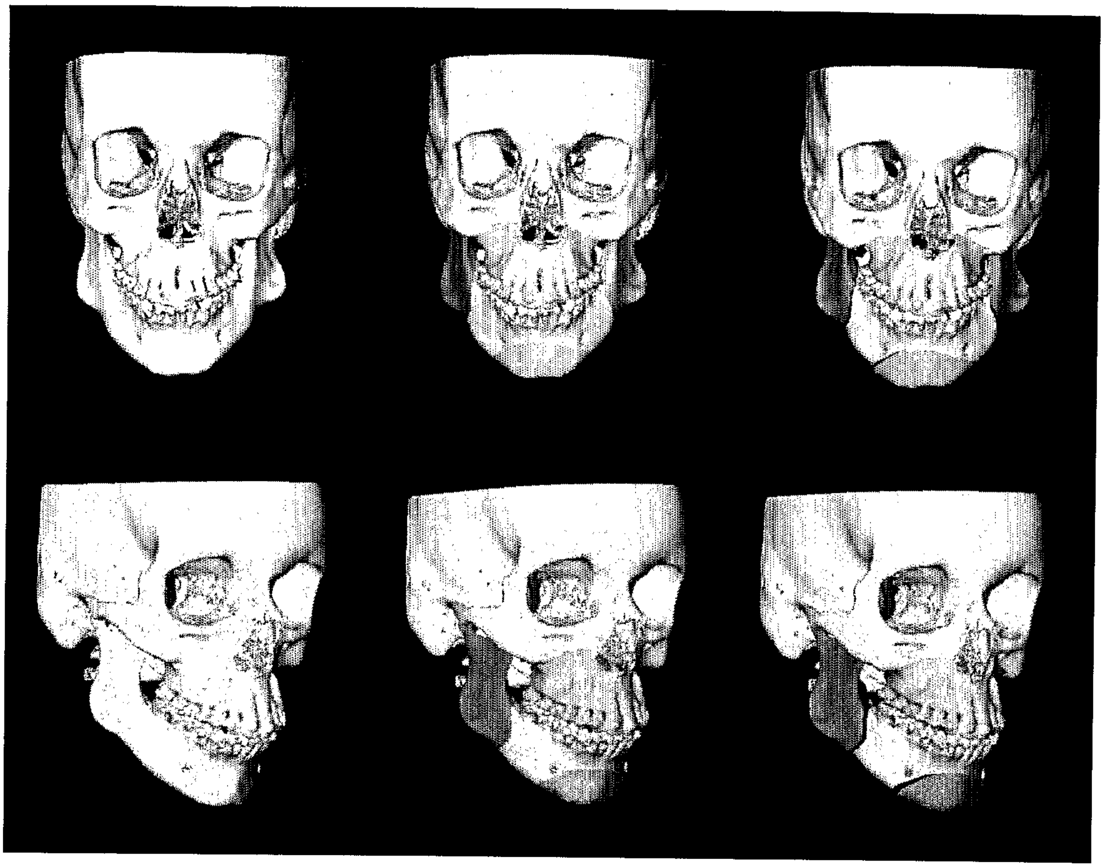


Fig. 9

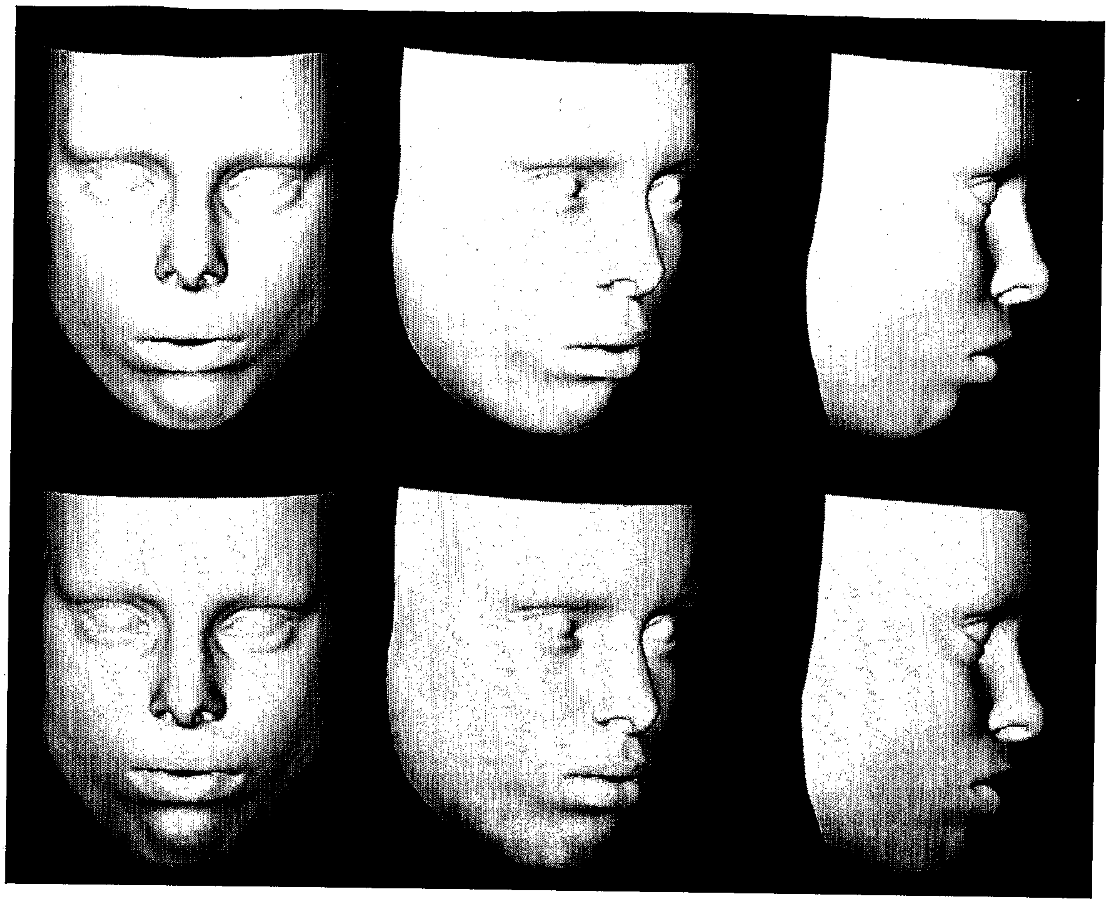


Fig. 10

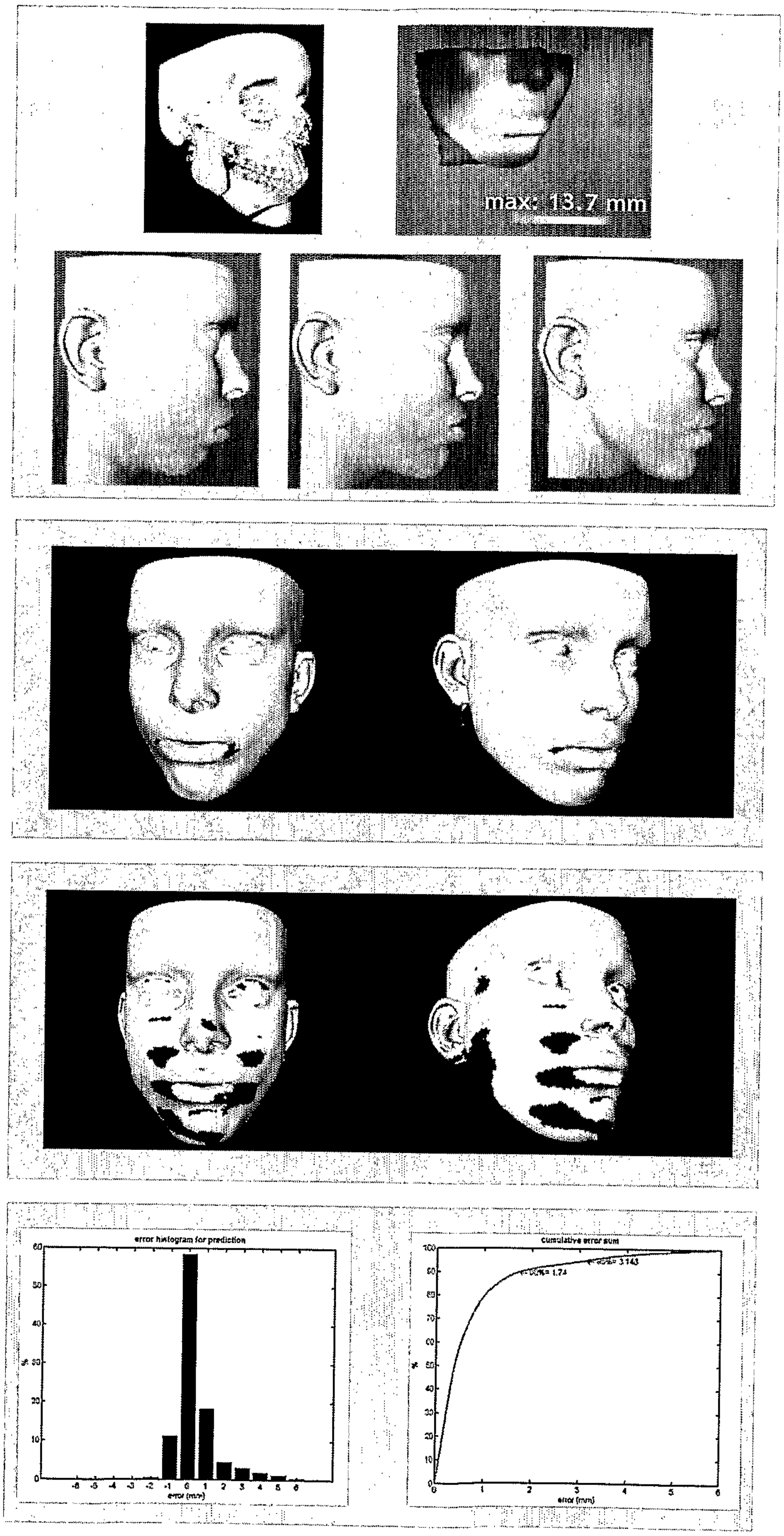
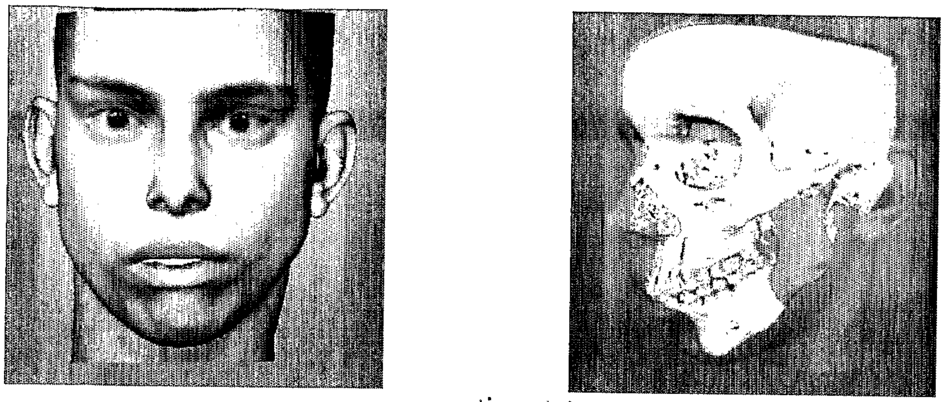
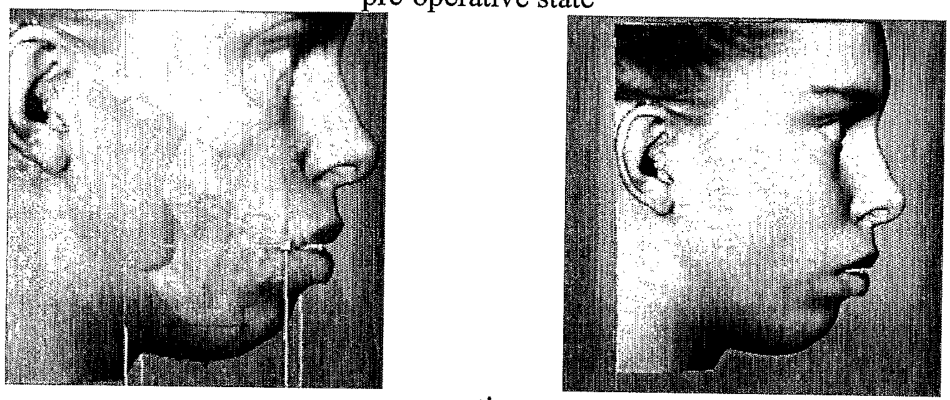

max: 13.7 mm
error histogram for prediction
cumulative error sum
error (mm)

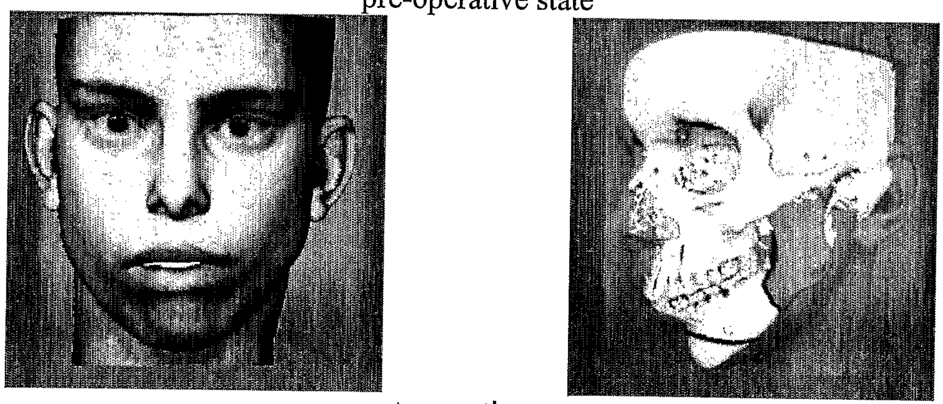
Fig. 11



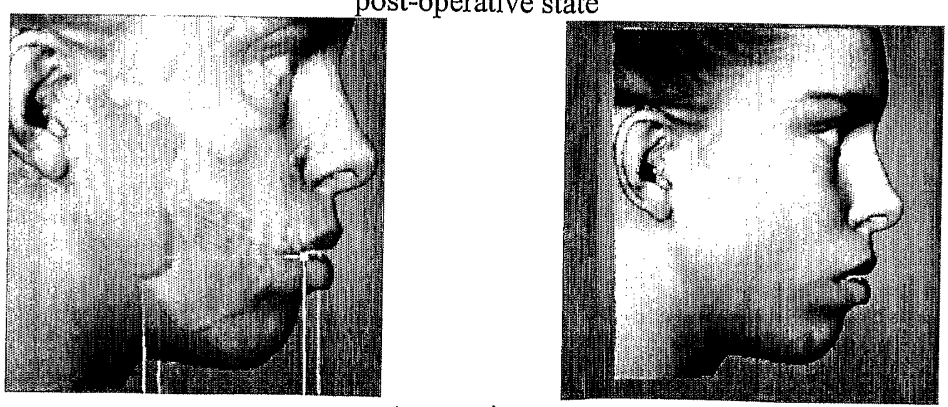
pre-operative state



pre-operative state



post-operative state



post-operative state

Fig.12

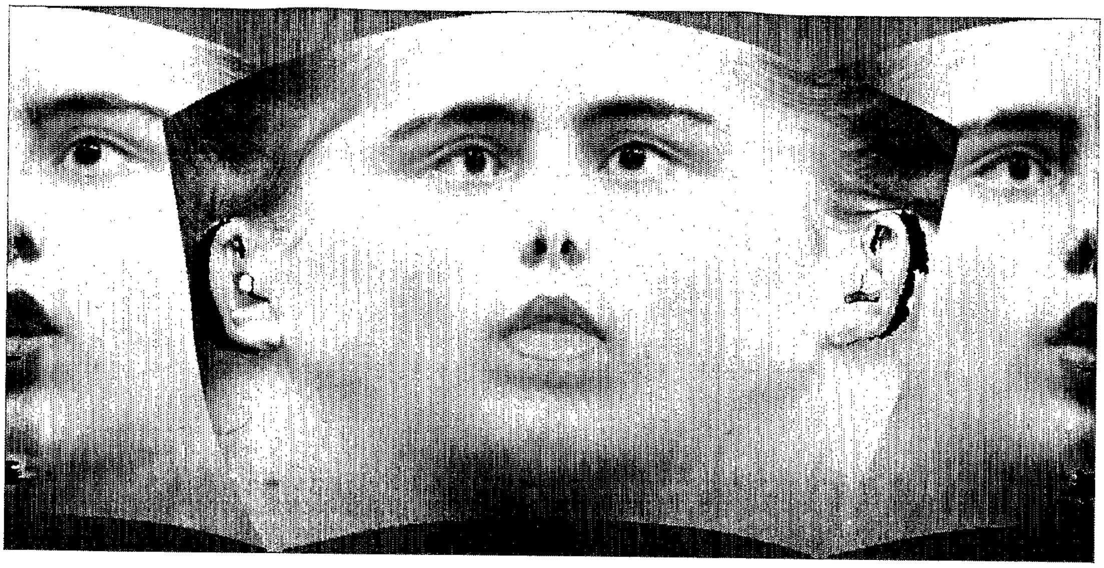


Fig. 13

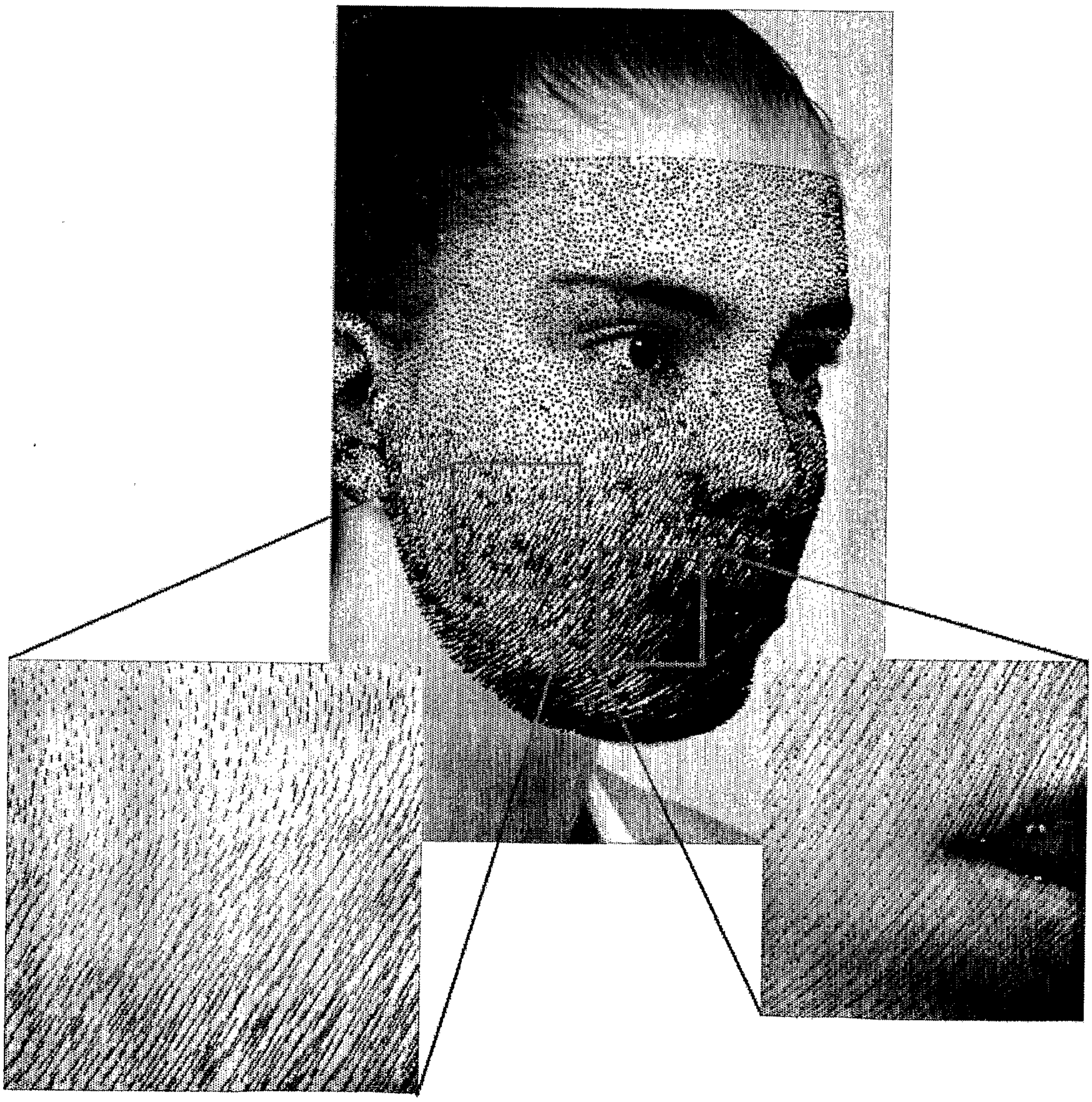


Fig. 14

Fig. 15

# INTERNATIONAL SEARCH REPORT

International application No
PCT/BE2006/000035

**A. CLASSIFICATION OF SUBJECT MATTER**
INV. G06T17/10

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
G06T G06F A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| P,X | US 2005/280644 A1 (IKEZAWA YOSHIKO) 22 December 2005 (2005-12-22) paragraph [0040] - paragraph [0046]; figure 2 | 1-11, 14-19 |
| X | XIA J ET AL: "THREE-DIMENSIONAL VIRTUAL REALITY SURGICAL PLANNING AND SIMULATION WORKBENCH FOR ORTHOGNATHIC SURGERY" INTERNATIONAL JOURNAL OF ADULT ORTHODONTICS AND ORTHOGNATIC SURGERY, QUINTESSENCE PUBLISHING, CAROL STREAM, IL, US, vol. 15, no. 4, 21 December 2000 (2000-12-21), pages 265-282, XP008032679 ISSN: 0742-1931 cited in the application | 1,3-11, 14-19 |
| Y | the whole document | 12,13 |

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 10 July 2006 | 22/08/2006 |

| Name and mailing address of the ISA/ | Authorized officer |
|---|---|
| European Patent Office, P.B. 5818 Patentlaan 2<br>NL – 2280 HV Rijswijk<br>Tel. (+31–70) 340–2040, Tx. 31 651 epo nl,<br>Fax: (+31–70) 340–3016 | Meinl, W |

Form PCT/ISA/210 (second sheet) (April 2005)

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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| A | YIP B ET AL: "An effective eye gaze correction operation for video conference using antirotation formulas" ICICS-PCM 2003. PROCEEDINGS OF THE 2003 JOINT CONFERENCE OF THE FOURTH INTERNATIONAL CONFERENCE ON INFORMATION, COMMUNICATIONS AND SIGNAL PROCESSING AND FOURTH PACIFIC-RIM CONFERENCE ON MULTIMEDIA (IEEE CAT. NO.03EX758) IEEE PISCATAWAY, NJ, USA, vol. 2, 2003, pages 699-703 vol.2, XP010701216 ISBN: 0-7803-8185-8 point 4. abstract | 2 |

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/BE2006/000035

| Patent document cited in search report | Publication date | Patent family member(s) | Publication date |
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| EP 1355277 A | 22-10-2003 | JP 2004157968 A | 03-06-2004 |
| | | US 2003218607 A1 | 27-11-2003 |