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Pose Estimation and Comparison of Painted Portraits using a 3D Head Model

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Abstract *We present a method to estimate the 3D pose of a painted head based on a 3D head model.The ellipsoid allows to estimate the shape or silhouette and the pose of the depicted head. By incorporating the symmetry property of a face the angle of rotation to the left or right is estimated. The head model is further used as a reference model to refer two faces of two different miniatures. A concept for comparing faces with different pose is discussed. Experimental results of the pose estimation method are reported.*

1 Introduction

A collection of nearly 600 portrait miniatures (for example see Figure 1) shows members and relatives of empress Maria Theresia and European dynasties. The collection was examined and sorted by art historians and classified into several groups according to historical and genealogical background. The miniatures originate from a period of 170 years in the 18th and early 19th century. There are groups of miniatures painted by one artist, groups showing the same person, groups of a certain time period and groups with genealogical and historical connections.

Figure 1: Miniature showing Maria Theresia

To overcome the artist identification problem, we gather expert knowledge of art historians and translate the knowledge into objective methods and procedures in order to build up a classification system. In [10] we proposed a hierarchical classification scheme for identifying the painting style, i.e. the “handwriting”, of an artist. The classification model is based on a 3D reference model of a human head, which allows to assign local artist dependent characteristics to facial regions. To establish this connection we have to determine the transformation from the 2D image of the head to the 3D reference model. This method can also be referred as 3D pose estimation from a single view.

In the following section we discuss methods for estimating the pose of human heads. A 3D head model allows to discriminate and to compare the artist’s technique independently of the various poses of the heads (Section 3). Section 4 shows the estimation of the pose using the silhouette and the symmetry property of the painted head. In Section 5 we discuss how to compare portraits by introducing artist-specific model. Experimental results and an outlook on future work conclude the paper.

2 Pose Estimation of Heads

Several studies to pose estimation of human heads have been discussed recently in the literature. One prominent approach is the appearance based approach (see e.g. [8]). Instead of an explicit object model, the appearance of an object is represented by a compressed set of images of varying poses of the image. Model based approaches usually have a 3D model representation of the object. The pose is calculated by finding a mapping between the 3D model and the 2D image. Examples for model based pose estimation of faces can be found in [5] [6] [7].

Due to the lack of a training set, which is necessary for an appearance based approach, we decided to use a geometric model for estimating the pose of the depicted faces. From the geometrical point of view we selected a model that is simple but able to represent the shape and view of 3D head. Therefore we choose an elliptical head model which is also used for head tracking [2] where simple models have to be used to guarantee real time tracking. The approximation of the head by a rotational ellipsoid was also inspired by the way the artist outlines the face by schematic, elliptical contour lines. They paint a person with a standard ”creation model” in mind [4], using an elliptical scheme, which determines shape and orientation of the head as well as the position of eyes, nose, cheeks and so on. Figure 2a gives an example of

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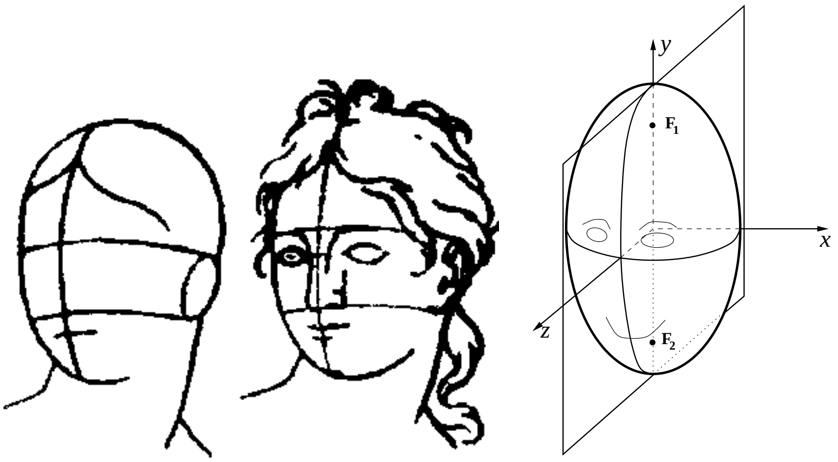


(a) (b)

Figure 2: (a) schematic heads from 18th century drawing books, (b) head model embedded in 3D coordinate system.

a schematic head from a drawing book of the 18th century [1].

Our method for pose estimation is a model based approach, which basically consists of two steps:

1. Reconstructing the ellipsoid from its projection by using the silhouette of the face
2. estimating the 3D rotation with respect to the main axis of the ellipsoid by using the symmetry property of the face

3 Ellipsoidal Head Model

For the geometrical configuration we used a right-handed Cartesian coordinate system (see Figure 2b) where the image plane coincides with the x-y-plane of the coordinate system. The rotation of the depicted heads with respect to the x-axis is very small. A reason therefore is the artists intention to show persons looking at the viewing person. The rotation angle is set zero and thus the rotational axis of the ellipsoid coincides with the y-axis. Any set of points on the surface of the ellipsoid $P = (x, y, z)$ fulfills the equation

$$x^2/b^2 + y^2/a^2 + z^2/b^2 = 1.$$

The variation of the 3D pose of the ellipsoid is restricted to a rotation about the y-axis and z-axis, the center of the ellipsoid remains in the center of the coordinate axis.

4 Estimating the Pose Using the Silhouette and Symmetry

A scaled orthographic projection maps the silhouette of the ellipsoid to the image plane. The result is equal to an intersection of the ellipsoid with the image plane, and therefore it is an ellipse. In our configuration the 3D ellipsoid can be reconstructed from the ellipse in the image plane straight forward, since ellipse and ellipsoid have the same semi-axis, the same origin, and the same rotation angle with respect to the z-axis.

The projection of the surface points of the ellipsoid into the image plane is not unique. Since we are just interested in the front of the head (the face), the image is defined as the projection of points with positive z-coordinate, $P = \{P_i\}_{i=0}^{n-1} = (x_i, y_i, z_i)$ with $z_i > 0$.

The remaining degree of freedom is the rotation of the ellipsoid with respect to the rotation axis (y-axis). To estimate the angle we use the property of a human face, which is almost symmetric with respect to an imaginary symmetry plane. This property holds for facial features like eyes, eyebrows, mouth, nose.

4.1 Finding the Silhouette

The silhouette of a face is approximated by an ellipse. In the experiments performed so far, the ellipse is fitted to a set of manually marked points, that are located on the face contour by minimizing algebraic distance $d = F(A, x_i)$ of a point x_i to the conic $F(A, x) = 0$ in a least square sense,

$$\hat{A} = arg \min_{A} \{ \sum_{i=1}^{N} F(A, x_i)^2 \}.$$

The conic is represented as

$$F(A, x) = Ax = ax^2 + bxy + cy^2 + dx + ey + f.$$

To solve the minimization problem we used an analytical solution suggested in [3]. Solving the general eigen system

$$Sa = D^T Da = \lambda Ca$$

where $D = [x1x2 \ldots xn]^T$ and C expresses the constraint $b^2 - 4ac = A^T CA = -1$ we obtain an eigenvector that corresponds to the single negative eigenvalue and contains the parameter A of the fitted ellipse.

4.2 Reconstruction of the Head

From the obtained ellipse parameters, the corresponding ellipsoid parameters can be calculated straight forward. The

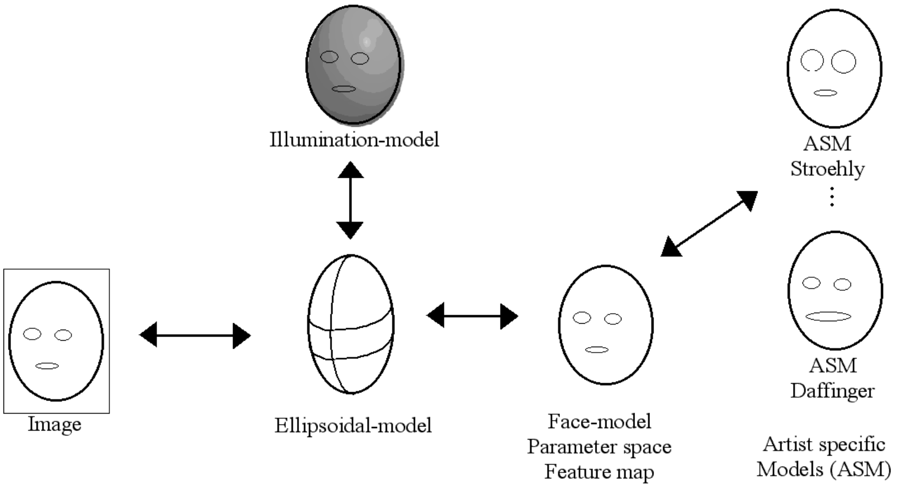


Figure 3: Artist specific model concept

center of the ellipsoid is located in the origin of the coordinate system. The length of the semi-axes of the ellipsoid are equal to the length of the semi-axes of the ellipsoid. The projected model points are rotated with respect to the z-axis by the negative rotation angle of the ellipse.

The 3D model points $\{P_i\} = (x_i, y_i, z_i)$ are calculated from 2D points $\{p_i\} = (x'_i, y'_i)$, which are located inside the ellipse and which are in normal position after the rotation, according to

$$\{P_i\} = (x_i, y_i, z_i) = (x'_i, y'_i, \sqrt{b^2 - {x'_i}^2 + {y'_i}^2 * a^2/b^2})$$

Since we are looking at the front side of the head, z is set to the positive result of the square-root.

4.3 Finding the Rotation using the Symmetry

To obtain the rotation angle with respect to the y-axis, the 3D points are rotated within a range from -90 to 90 degrees. For each angle within that range (the sampling determines the accuracy of the method) the points are projected into the image plane and a measure for the symmetry with respect to the y-axis is calculated. The angle corresponding to the "most symmetric" point configuration is the estimated rotation angle.

To measure the symmetry we use the symmetry distance measure which was presented in [11]. The symmetry distance (SD_Z) handles symmetry as a continuous feature by measuring the distance between a set of points $P = \{P_i\}_{i=0}^{n-1}$ and its symmetry transform $Q = \{Q_i\}_{i=0}^{n-1}$ using the metric

$$SD_Z = \frac{1}{n}\sum_{i=0}^{n-1} ||P_i - Q_i||.$$

The range of the SD_Z value can be limited by zero for a perfect symmetric configuration and an upper bound by the maximum distance of the points and the centroid of the points.

The symmetry transform is defined on pairs of points. We therefore split the set of projected points p=$\{p_i\}$ into 2 subsets $\{p_i^-\} = (x_i^-, y_i^-)$ and $\{p_i^+\} = (x_i^+, y_i^+)$ with $x_i^- < 0$ and $x_i^+ > 0$.

An extension of the measure was necessary since the presented method was defined for two set of the same cardinality. Since we divide the set p into 2 subsets that need not have the same cardinality we extended the measure as follows

$$SD = (1 - \alpha) * SD_Z + \alpha * rest$$

where $rest$ is the number of points with no corresponding point in the smaller subset and α a weighting parameter.

Finding the "most symmetric" point configuration is performed by minimizing the SD value over all rotations.

5 Comparing Portraits using Artist Specific Models

To classify the portrait miniatures we develop artist specific models which identify the artist specific characteristics:

- proportions of eyes, nose, mouth
- stroke parameters (length, orientation, color...)
- illumination (shadowed vs. not-shadowed half of the face)

To relate the characteristics of a group of portraits independent from the pose the ellipsoid model is used as the reference-model using the following properties:

1. Every point on the ellipsoidal surface is determined by two parameters (s, t), e.g. two angles measured from the center or latitude and longitude as used to identify a point on the earth.
2. The image of a face is assumed as an orthogonal projection of the model determined by the projection parameters. Arbitrary points (s,t) on the ellipsoidal surface can be connected with the corresponding points x(s,t), y(s,t), z(s,t) in the 3D coordinate system.

3. The person depicted in the miniature shows specific face proportions. To obtain face measurements distances (and possibly angles) are computed from facial features [9]. Some important measures from the art historical point of view are: the size of the eyes, the width and shape of the mouth, distance between eyes and nostrils, distance between nostrils and mouth.

4. Artist specific modulation of these parameters (e.g. a typical characteristic of a painter are oversized eyes) and the specific painting technique applied to specific areas of the face (e.g. stroke type of eye brows) are mapped from the image to the reference-model and compared independently of projection on this reference-model.

5. The model further allows the reconstruction and the simulation of an illumination situation that can be observed in the face image by mapping radiometric information to every point in the parameter space (e. g. 3D surface normal, pixel shading, light source).

In Figure 3 the framework for building up artist specific models is illustrated. In the connection between image and model every pixel of the image is assigned to a corresponding point in the parameter space. Artist specific parameters obtained from the stroke detection like stroke-length(s,t), stroke-orientation(s,t) and color information (color(s,t)) are represented in the parameter space. So individual parameters map into feature maps for every image.

When developing artist specific models it must be considered, that the observed features need not only be characteristic for an artist but can also be a characteristic of the depicted person. By analyzing a group of miniatures which show portraits of one person, differences in the painting style can be elaborated. The analysis of signed portraits will be of importance in the design of an artist specific model.

6 Experiments for Pose Estimation

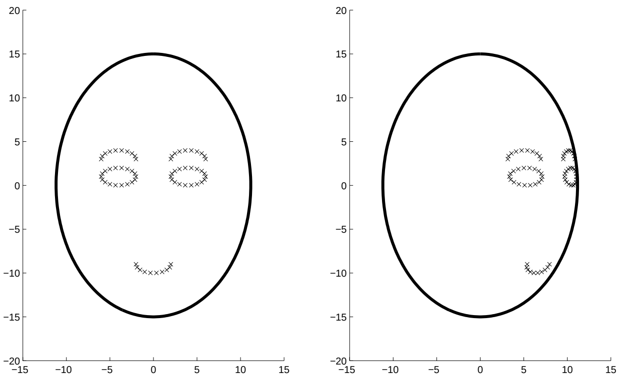
We have experimented with an artificial data set and a subset of the miniatures in our collection.

6.1 Experiments with Artificial Data

In a first experiment the estimation of the rotation angle was tested with artificial data. We built a 3D model of a face consisting of 66 points that are arranged like a schematic face.

To simulate different views of known orientation, the 3D model is rotated from -90 to 90 degrees with steps of 10 degrees. For each rotation the 3D model points are projected into the 2D image plane, which are the input to our method. Two input examples, one for 0 and one for 50 degree can be seen in Figure 4.

In Figure 5 the resulting SD values of the experiment are visualized. The curves for angles greater than zero degrees have analogous values. One curve represents the SD values that are calculated during the rotation of on point set. The minimum SD value is the obtained negative rotation angle of the head model. For reasons of clarity only some representative curves are depicted in the figure.



(a) (b)

Figure 4: Projected model points (a) 0 degree (b) 50 degree .

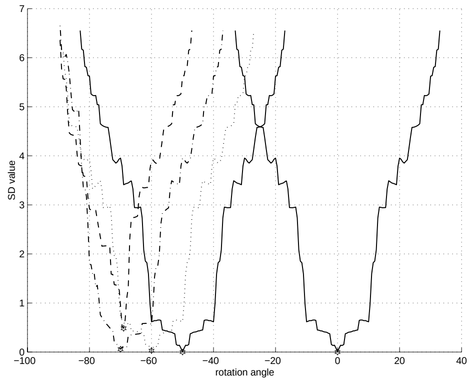


Figure 5: Selected curves of SD value for angles 0,50,60,70,80 and 90 degrees.

The method provides correct results within an angular range from -70 to 70 degrees. Angles outside this range lead to errors. The reason therefore is, that some of the rotated points lie in the "back-half" of the ellipsoid and are eliminated from the input set.

The exact data of the experiment are listed in the following table. The first row shows the actual angle, the second row the estimated angle and its corresponding SD value.

actual angle	0	...	50	60	70	80	90
estimated angle	0	...	50	60	70	69	72
min SD	0	...	0	0.03	0.06	0.48	0.35

Table 1: Estimated angles from the artificial setup

6.2 Experiments with Portrait Images

If the method is applied to portrait images, some preprocessing steps are necessary.

1. First, contour points for the ellipse fitting are selected manually.

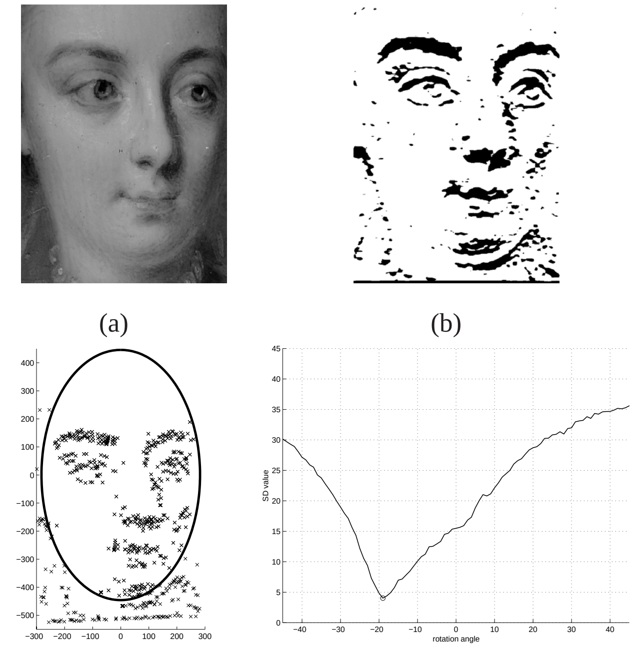
2. In a next step the influence of brush strokes for the edge detection process. is eliminated. Since the brush strokes

do not necessarily provide symmetric patterns, the image is preprocessed by a Gaussian filter $G(\sigma, \mu)$ where σ is chosen $\sigma = 3\times$ average brush stroke width.

3. Horizontal edges are detected with the horizontal Sobel filter. Horizontal edges are preferred to vertical edges which are emphasizing non-symmetric regions like the nose, pupils. More strictly, we should detect edges parallel to the major ellipse axis, which is given in most cases of our data set.

4. The input points are obtained by thresholding and subsampling of the edge-magnitude image. The setting of threshold is set empirically to 15%.

In Figure 6a an image of one of our miniatures is depicted, Figure 6b shows the edges after thresholding and Figure 6c the fitted ellipse and the set of points selected from the edge image. Finally the curve of the obtained SD values is depicted in Figure 6d, with a rotation angle of 19 degree and a corresponding minimal SD value of 4.024.



(a) (b)

(c) (d)

Figure 6: (a) gray-value image of a miniature (b) preprocessed image (c) fitted ellipse and selected input points (d) obtained SD values.

6.3 Experiments with a head moulded of clay

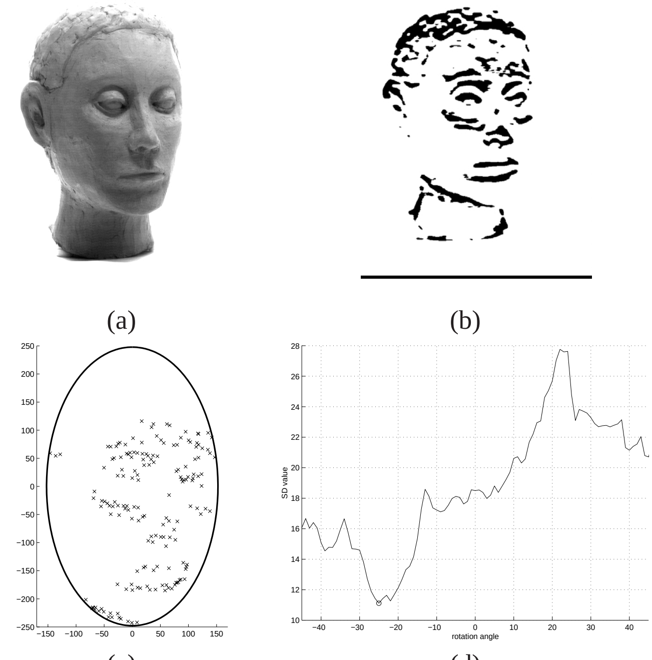
Due to the lack of ground truth information of the actual pose of the heads depicted in the miniatures, we experimented with an artificial head molded of clay. Using a turntable the head was acquired within the angular range from 0 to 90 degree. Figure 7 shows the example (analogous to Figure 6) for an angle of 25 degrees.

Additionally to the presented method, we calculated the angle directly, by manually selecting a point which is located on the intersection of ellipsoid and symmetry plane (in our experiments the point below the nose tip). The calculated angles are listed in Table 2, where the first column represents the actual values, the second column the values calculated with the manual points, and the third column the results of our method.

The divergencies between the actual values and the results from symmetry method depend on the selection of symmetric points. In case of the arificial head the illumination influences the edge detection and thus the set of points that are the input for the algorithm.

actual angles	manual	symmetry
0	0	1
5	5.9	3
10	10.6	16
15	17.5	19
20	23.4	24
25	27	25
30	31.5	29
35	36.7	31
40	42.3	39
45	44.3	34
50	49.3	33

Table 2: Comparison between actual angles, angles calculated with the manual method and the symmetry method (all values in degrees).



(a) (b)

(c) (d)

Figure 7: (a) gray-value image of the head (b) preprocessed image (c) fitted ellipse and selected input points (d) obtained SD values.

7 Conclusion and Outlook

We proposed a system to compare faces of painted portraits of different view. The heart of the system is a 3D model which is used to estimate the pose of a human head from a single 2D. The method incorporates a rotational ellipsoid as the head model, which is used for calculating the shape of the head from its silhouette. The remaining degree of freedom, the rotation with respect to the z-axis, is estimating by using the symmetry property of a face. Results for pose estimation with artificial data and real images of miniatures have shown satisfying results. Nevertheless, the most crucial part when applying the method to real images is the selection of the points.

The next goal is to build up artist-specific models by an intensified comparison of selected miniatures. The presented framework consisting of the 3D model and the mapping to individual painted heads allows to compare artist specific characteristics within facial regions. From a comparison of certain facial regions (e.g. eyes, cheeks) we expect a significant discrimination of painted portraits.

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