Tracking a face for knowledge-based coding of videophone sequences

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face during the sequence using the face model (face tracking).

Recently, adaptation of the face model Candid onto the person’s face in a knowledge-based coder has been investigated [9, 12, 21]. In these approaches, at the beginning of the sequence the person’s face is first detected using template matching and feature extraction techniques. Then, the face model Candid is adapted to the size of the person’s face and integrated into the 3D model object which describes the real object.

For face tracking during the sequence, several algorithms based on global head motion compensation under the assumption of a rigid face model have been proposed [5, 9, 14, 18, 23]. In [18, 23], motion compensation is based on extracting 2D correspondences, e.g. feature points or contours. Here, the locations of the feature points or contours have to be estimated first. Then, the 3D motion of the head is determined from these 2D correspondences in two successive frames under the assumption of a rigid face model. Hence, mismatching of the 2D correspondences directly affects the accuracy of face tracking. The other methods estimate the 3D head motion, i.e. rotation and translation, from two successive frames using the optical flow constraint equation [5, 9, 14]. Because the accuracy of the 3D motion estimation of the head is affected by the 3D model shape, the inaccurate 3D model shape reduces the accuracy of face tracking. In order to overcome the effects of inaccurate 3D model shape on the 3D motion estimation, several algorithms for the update of the face model’s shape have been proposed [3–5, 13]. In [4, 5, 13], a depth update of the face model based on the optical flow constraint equation is proposed. In [3], the 3D motion and the 3D coordinates of the vertices of the face model are simultaneously estimated including photometric effects. Extensive overviews on this topic can be found in [1, 2, 6, 15, 22].

In this paper, an algorithm for tracking a face using the face model Candid for knowledge-based coding of videophone sequences is presented, which combines global head motion compensation and the update of the face model’s shape during the sequence. For shape update, not only the eye and mouth center points of the face model are adapted to match the positions of the real eye and mouth in

the sequence but also the orientation of the face model is updated. The proposed algorithm differs from the previous works in the following two aspects: (1) a flexible face model is used where the face model is adapted from frame to frame based on the estimated 3D eye and mouth center positions, in opposition to [9] where a rigid face model is used which is adapted only once at the beginning of the sequence; (2) compared to [3–5, 13], only the 3D eye and mouth center positions are estimated for the update of the face model’s shape. The other vertices of the face model are moved based on these estimated 3D positions.

The paper is organized as follows. Section 2 briefly introduces the concept of a KBASC, the proposed face tracking system and the face model Candid. Section 3 reviews the global head motion compensation used in [9]. Section 4 discusses how the 2D eye and mouth center positions of the person’s face in the image plane are estimated. Section 5 explains how from these 2D center positions first estimates of the 3D eye and mouth center positions can be derived. Section 6 reports how the final estimates of these 3D center positions are obtained by considering the face model’s orientation. Experimental results with synthetic images and typical head-and-shoulder videophone sequences are given in Section 7.

2. KBASC, face tracking scheme and face model Candid

In this section, the concept of KBASC, the whole face tracking scheme, and the face model Candid used in this paper are addressed.

2.1. Concept of KBASC

KBASC tries to map a model world to the real world. The 3D real objects of the real world are captured by a real camera. This camera is modeled by a static pinhole model camera (Fig. 1), which looks into a 3D model world. In this model world, each moving real object is described by an opaque, diffusely reflecting moving 3D model object. The shape of the model object is represented by a 3D
wireframe (vertices) including predefined wireframe models. Each model object in the model world is described by three parameter sets defining the motion, shape and surface color of an object. The parameter sets of each model object are estimated by an image analysis. For head-and-shoulder scenes, KBASC [9] uses a predefined face model Candide to achieve a better modelling of the human face and exploits the knowledge of the face location for subjectively tuned bit allocation, so that the coding efficiency is improved compared to OBASC. A KBASC does not make use of the knowledge about the human facial expressions. If knowledge about facial expressions is available, it can be exploited by extending a KBASC to a semantic coding system [17].

2.2. Face tracking scheme

The proposed complete face tracking scheme consists of the following six steps (Fig. 2): the first step is tracking by global head motion compensation under the assumption of rigidity of the moving 3D objects as used in [9]; the second step gives the estimates of 2D center positions of the eyes and the mouth in the image plane; the third step deals with the estimation of the 3D center positions of the eyes and the mouth from the 2D eye and mouth center positions estimated in the second step; with these 3D estimates the face model's position and size is updated; the next step estimates the 3D eye center positions along the view lines; with these estimates finally the face model's orientation is updated. In this face tracking system, the first step gives a coarse face tracking and the other steps aim at a refined face tracking by updating the face model's shape.

2.3. Face model Candide

For the face model Candide (Fig. 3), its shape parameters are only the 3D center positions of the
corresponding 3D positions before the update, respectively. An arbitrary point \( P^{(i)} \) on the surface of the face model moves to its new position \( P^{*^{(i)}} \) as follows: at first, the face model is shifted with the translation vector \( T^b \) so that the center \( P^o \) between both eyes coincides with the origin of the 3D coordinate system; after this, the face model is rotated according to the 3D rotation angles, \( R^b_0 = (R^b_x, R^b_y, R^b_z)^T \), scaled according to the scale factor \( S = (S_x, S_y, S_z)^T \), and rotated according to the 3D rotation angles \( R^a_0 = (R^a_x, R^a_y, R^a_z)^T \); finally, it is shifted with the translation vector \( T^a \) to its new position. Thus, this motion can be formulated as

\[
P^{*^{(i)}} = [R^b_0] [S] [R^a_0] (P^{(i)} - T^b) + T^a,
\]

with the rotation matrices \([R^b_0]\) and \([R^a_0]\), and the scale factor matrix

\[
[S] = \begin{bmatrix}
S_x & 0 & 0 \\
0 & S_y & 0 \\
0 & 0 & S_z
\end{bmatrix}.
\]

The superscripts a and b denote after and before scaling, respectively. The scale factors \( S_x, S_y \) and \( S_z \) along the x-, y- and z-axis are calculated from the shape parameters of the face model, i.e. 3D center positions of the eyes and the mouth,

\[
S_x = \frac{\|P_x^{*^e} - P_x^{*^r}\|}{\|P_x^r - P_x^l\|},
\]

\[
S_y = \frac{\|P_y^{*^m} - P_y^{*^o}\|}{\|P_y^o - P_y^m\|},
\]

\[
S_z = \frac{1}{2}(S_x + S_y).
\]

The rotation angles \( R^b_x \) and \( R^a_x \) are calculated as

\[
R^b_x = - \arctan \left( \frac{P_m^x - P_o^x}{P_m^y - P_o^y} \right),
\]

\[
R^a_x = \arctan \left( \frac{P_m^x - P_o^x}{P_m^y - P_o^y} \right).
\]

In the same way, the other rotation angles \( R^b_y, R^a_y, R^b_z, R^a_z \) can be calculated from the 3D eye and mouth center positions.
3. Global head motion compensation

As a first step of the algorithm proposed in this paper, the method of face tracking by global head motion compensation based on 3D rigid moving objects as used in [9] is applied. This method is reviewed in this section.

In [9], the face location and the silhouette of the person are exploited to generate a model object with head and shoulders (Fig. 4). The head includes the face model Candide. The knowledge about the face location is used to control the subdivision of the model object into head and shoulders. It is shown in [16] for OBASC that this subdivision can improve the 3D motion compensation especially when head and shoulders move differently. Furthermore, the face model matches the shape of a real person’s face better than the generalized cylinder used by OBASC [16, 19]. Thus, 3D motion compensation of a KBASC should be superior to that of an OBASC [9].

3D motion estimation minimizes the mean square luminance difference between the model image and the real image. It is assumed that object components are rigid and have diffusely reflecting surfaces. Furthermore, diffuse illumination of the scene is assumed. Hence, color parameters are temporarily constant. Based on these assumptions, the luminance differences between two consecutive images $s_k$ and $s_{k-1}$ are due to object motion. For minimization of the luminance differences, an approach with a linearized signal model was developed in [10, 11] and further improved in [19]. According to [25], this method is not much sensitive to illumination effects. The luminance differences at position $P^{(j)} = (P_x^{(j)}, P_y^{(j)}, P_z^{(j)})$ of the observation point $Q^{(j)} = (P_x^{(j)}, s^{(j)}, F^{(j)})$ on the head model surface with $N$ control points (vertices) $P^{(j)}$ is related to motion parameters by the following linearized equation where the superscripts $(j)$ are omitted for better readability [11]:

$$
\Delta I = F \frac{g_x}{P_z} T_x^h + F \frac{g_y}{P_z} T_y^h - [\left( P_x g_x + P_y g_y \right) F/P_z^2 + \Delta I/P_z] T_x^h
$$

$$
- \left[ \left( P_x g_x (P_x - C_x^h) + P_y g_y (P_y - C_y^h) \right) F/P_z^2 + \Delta I/P_z (P_x - C_x^h) \right] R_x^h
$$

$$
+ \left[ \left( P_y g_y (P_y - C_y^h) + P_x g_x (P_x - C_x^h) \right) F/P_z^2 + \Delta I/P_z (P_y - C_y^h) \right] R_y^h
$$

$$
- \left[ g_x (P_x - C_x^h) - g_y (P_y - C_y^h) \right] F/P_z R_x^h,
$$

(3.1)

with the unknown motion parameters of the head model $T^h = (T_x^h, T_y^h, T_z^h)^T$ and $R^c = (R_x^h, R_y^h, R_z^h)^T$.

![Model scene and model object CLAIRE subdivided into the two flexibly connected components head and shoulders. The component head contains the face model Candide: (a) scene consisting of two objects; (b) components of model object CLAIRE.](image-url)
the head model center \( C^h = (C^h_x, C^h_y, C^h_z) = (1/N) \times \sum_{i=1}^{N} P^i_c \) and the linear gradients \( g^{(j)} = (g^{(j)}_x, g^{(j)}_y, g^{(j)}_z)^T \) at position \( P^{(j)} = (P^{(j)}_x, P^{(j)}_y, P^{(j)}_z)^T \). The residuum of this equation system is minimized by linear regression:
\[
\sum_{(i,j)} (\Delta t^{(j)})^2 \rightarrow \text{MIN.} \tag{3.2}
\]

Due to the linearization, the motion parameters have to be estimated iteratively. After that, the motion of the face model Canside is compensated.

4. Estimation of the 2D center positions of the eyes and the mouth in the image plane

For estimation of the 2D center positions of the eyes and the mouth, an approach in [9, 12, 21] is presented only for adaptation of the face model once at the beginning of the sequence. Here, this approach is also used for tracking a face during the sequence and extended in several respects in order to achieve a reliable and more precise estimation of the eye and mouth center positions. The elements of the improved method are discussed in this section.

4.1. Selection of the potential eye and mouth areas

Fig. 5 illustrates how the potential eye and mouth areas are selected. This method differs from that used in [9, 12, 21]. After global head motion compensation, the location of the face model projected onto the image plane is already a good approximation of the face location in the real image. Therefore, compared to the large search areas used in [9, 12, 21], for simplicity smaller search areas for the eyes and the mouth are determined here by exploiting the projected positions of the eyes and the mouth of the face model onto the image plane. By this, the correct center positions of the eyes and the mouth can be found more often and the search areas can be essentially diminished. After that, in order to further reduce the search areas for the eyes and the mouth, template matching is used in which the eye and mouth templates are the same as those used in [9, 21]. The eye template is an open eye and has 23 \( \times \) 13 picture elements. The mouth template has 31 \( \times \) 21 picture elements. These templates are then roughly adapted to the size of the person’s face. In contrast to [9, 12, 21], here the templates are additionally inclined in accordance with the inclination of the head. The inclination of the person’s head is defined as
\[
\beta = \arctan \left( \frac{Y_i - Y_r}{X_i - X_r} \right), \tag{4.1}
\]
where \((X_i, Y_i)\) and \((X_r, Y_r)\) are the projections of the left eye and the right eye of the face model after global head motion compensation onto the image plane. For a point \((X, Y)\) in the eye search areas, the correlation coefficient \(c_{\text{eye}}(X, Y)\) between the real image \(s_0\) and an eye template \(t_{\text{eye}}\) is computed in a window centered at the corresponding point
(X, Y) in the real image s_k. The correlation coefficient \( c_{\text{eye}}^k (X, Y) \) is defined as follows:

\[
c_{\text{eye}}^k (X, Y) = \frac{E(s_k t_{\text{eye}}) - m_s m_{t_{\text{eye}}}}{\sigma_s \sigma_{t_{\text{eye}}}}
\]

(4.2)

where \( E() \) is a mean operation, \( m_t, \sigma_t^2 \), and \( m_s, \sigma_s^2 \) are the means and variances of the eye template \( t_{\text{eye}} \) and the real image \( s_k \) in the window which is as large as the eye template, respectively. The higher the value \( c_{\text{eye}}^k (X, Y) \), the higher is the probability that this point \((X, Y)\) in the eye search areas is the 2D eye center point. Points with high values of \( c_{\text{eye}}^k (X, Y) \) are extracted as the potential areas for eyes. By this, the search areas for eyes are further reduced. In the same way, the mouth search area can be also reduced. The subsequent algorithms for estimation of eye and mouth center positions are applied only to these potential areas which might contain the eyes and the mouth.

4.2. Estimation of the 2D eye center positions

The pupil is defined as the center of the eye. Because the pupil of an eye is darker than the rest of the eye, a measure \( f_{\text{eye}} \) is evaluated within the potential areas for eyes:

\[
f_{\text{eye}} = \frac{255 - s_k (X, Y)}{255}.
\]

(4.3)

This measure assigns a high value to dark pels \((X, Y)\) of the real image \( s_k \). Those two points with the highest values of \( f_{\text{eye}} \) are selected as 2D eye center positions.

4.3. Estimation of the 2D mouth center position

For estimation of the mouth center position, a measure \( f_{\text{mouth}} \) is evaluated:

\[
f_{\text{mouth}} = c_{\text{mouth, size}}^k (X, Y),
\]

(4.4)

where \( c_{\text{mouth, size}}^k (X, Y) \) are the correlation coefficients between the real image \( s_k \) and a mouth template. In contrast to Section 4.1, additional scaled templates with scale factors 0.8, 0.9, ..., 1.4 are evaluated. The point with the highest values of \( f_{\text{mouth}} \) is selected as 2D mouth center position.

5. Estimation of the 3D eye and mouth center positions in the eye–mouth plane and update of the face model’s position and size

After the 2D center positions of the eyes and the mouth have been estimated as described in Section 4, the 3D center positions in the eye–mouth plane can be derived \[26\]. If the 2D center positions of the eyes could not at all be estimated, e.g. if the eyes are closed, no update of the face model's position and size is performed. In these situations, only global head motion compensation is applied for tracking the face. For the update of the face model’s position and size during the sequence, the new 3D eye and mouth center positions of the face model have to be calculated by means of those 2D center positions just estimated. This problem is addressed in the following sections.

5.1. Overview of the calculation of the 3D eye and mouth center positions of the face model Candide

Since the true depths of the eyes and the mouth are unknown, the calculation of the new 3D center positions of the eyes and the mouth is based on the following two assumptions:

1. 3D center positions of the eyes and the mouth are in the same eye–mouth plane before and after the update of the face model's position and size;
2. 3D center positions of the eyes and the mouth span an isosceles triangle (Fig. 6) in the eye–mouth plane.

The projections of the 2D center positions of the eyes and the mouth estimated as described in Section 4 from the image plane onto the eye–mouth plane of the face model may not fulfill the second assumption. Because of a more precise estimation of the eye positions than of the mouth position in the image plane, the new 3D eye center positions of the face model will be calculated first. After that, the new 3D mouth center positions of the face model are calculated according to the second assumption.
5.2. Calculation of the new 3D eye center positions of the face model

The projections of the estimated 2D eye center positions from the image plane onto the eye–mouth plane are taken as the new 3D eye center positions. According to the first assumption, the eye–mouth plane can be determined as follows:

\[
\begin{pmatrix}
X - X_e & Y - Y_e & 1 & 0 & 0 \\
X' - X_e & Y' - Y_e & 1 & 0 & 0 \\
X'' - X_e & Y'' - Y_e & 1 & 0 & 0
\end{pmatrix}
= 0,
\]

where \( P^n = (P^n_x, P^n_y, P^n_z) \), \( P' = (P'_x, P'_y, P'_z) \), and \( P'' = (P''_x, P''_y, P''_z) \) are the 3D center positions of the mouth, the left eye and the right eye of the face model after global head motion compensation, respectively. \( P = (P_x, P_y, P_z) \) is an arbitrary point in the eye–mouth plane. The new 3D eye center positions \( P' = (P'_x, P'_y, P'_z) \) and \( P'' = (P''_x, P''_y, P''_z) \) to be calculated must satisfy a perspective projection of a static pinhole camera,

\[
P'_x = \frac{X'_e}{F} P'_z, \quad P'_y = \frac{Y'_e}{F} P'_z
\]

and

\[
P''_x = \frac{X''_e}{F} P''_z, \quad P''_y = \frac{Y''_e}{F} P''_z,
\]

where \( F \) is the focal length of the model camera, \((X'_e, Y'_e)\) and \((X''_e, Y''_e)\) are the estimated 2D center positions of the left eye and the right eye. The value \( F \) is known in the model camera. Substituting (5.2) into (5.1) gives the z-coordinate of the left eye

\[
P'_z = F \frac{P''_x J_{11} + P''_y J_{12} + P''_z J_{13}}{X'_e J_{11} + Y'_e J_{12} + F J_{13}},
\]

where \( J_{11}, J_{12}, \) and \( J_{13} \) are the subdeterminants of the determinant in (5.1). After \( P'_z \) is calculated, \( P'_x \) and \( P'_y \) of the left eye can be derived from (5.2). Also, the z-coordinate \( P''_z \) of the right eye can be similarly obtained by substituting (5.3) into (5.1), i.e.

\[
P''_z = F \frac{P'x J_{11} + P'y J_{12} + P'z J_{13}}{X''_x J_{11} + Y''_x J_{12} + F J_{13}}.
\]

Substituting \( P'_z \) into (5.3) gives the coordinates \( P'_x \) and \( P'_y \) of the right eye.

5.3. Calculation of the new 3D mouth center positions of the face model

Calculation of the new 3D mouth center positions of the face model is more complex than that of the eyes. According to the second assumption, the new 3D mouth center position \( P'^m = (P'^{m}_x, P'^{m}_y, P'^{m}_z) \) to be calculated lies on the perpendicular bisecion \( L_{om} \) of the line \( P'^{e}P'^{e} \) between both new 3D eye positions (Fig. 7(a)). This line \( L_{om} \) is projected onto the image plane. Here, the projected line \( l_{om} \) intersects a parallel \( l_{mouth} \) of the line \( l_{eye} \) which connects both estimated 2D eye positions in the image plane (Fig. 7(b)). This parallel \( l_{mouth} \) goes through the estimated 2D mouth position in the image plane. The projection of this intersection point \( p'^{m} \) from the image plane onto the eye–mouth plane gives the new 3D mouth center positions \( P'^{m} \) (Fig. 7(a)).
Fig. 7. Calculation of the new 3D mouth center position of the face model. (a) Calculation of the perpendicular bisection of \( P_l^r \) and \( P_r^r \) and projection onto the image plane; projection of \( P^m \) onto the eye–mouth plane. (b) Update of the estimated mouth center position.
Due to the first assumption, the calculated 3D mouth center positions must satisfy (5.1) and due to the second assumption, the equation

\[
(P_x' - P_x^o)(P_x^m - P_x^o) + (P_y' - P_y^o)(P_y^m - P_y^o) + (P_z' - P_z^o)(P_z^m - P_z^o) = 0,
\]

where \(P_x^o, P_y^o, P_z^o\) is the center point of both new 3D eye positions \((P_x', P_y')\) calculated as described in Section 5.2, and

\[
P_x^m = \frac{X_m + \Delta X}{F} P_x^m, \quad P_y^m = \frac{Y_m + \Delta Y}{F} P_y^m, \quad P_z^m,
\]

where \((\Delta X, \Delta Y)\) (Fig. 7(b)) are the deviates from the 2D mouth center positions \((X_m, Y_m)\) estimated as described in Section 4. \(\Delta X\) and \(\Delta Y\) fulfill the following equation:

\[
\frac{\Delta Y}{\Delta X} = \frac{Y_r - Y_t}{X_r - X_t} =: \tan \alpha,
\]

with \(\alpha\) being the inclination angle of \(l_{\text{mouth}}\) (Fig. 7(b)).

Eq. (5.7) stands for a perspective projection of a static pinhole camera. Using (5.1) and (5.6)–(5.8) gives the z-coordinate \(P_z^m\) of the mouth

\[
P_z^m = F \frac{c_1 c_5 - c_3 c_6}{c_2 c_5 - c_4 c_6},
\]

and

\[
\Delta X = \frac{c_2 c_3 - c_1 c_4}{c_1 c_5 - c_3 c_6},
\]

where

\[
c_1 := P_x^o (P_x' - P_x^o) + P_y^o (P_y' - P_y^o) + P_z^o (P_z' - P_z^o),
\]

\[
c_2 := X_m (P_x' - P_x^o) + Y_m (P_y' - P_y^o) + F (P_z' - P_z^o),
\]

\[
c_3 := J_{11} P_x^m + J_{12} P_y^m + J_{13} P_z^m,
\]

\[
c_4 := J_{11} X_m + J_{12} Y_m + J_{13} F,
\]

\[
c_5 := J_{11} + J_{12} \tan \alpha,
\]

\[
c_6 := (P_x' - P_x^o) - (P_y' - P_y^o) \tan \alpha.
\]

Substituting (5.10) into (5.8) gives \(\Delta Y\). Then, the coordinates \(P_x^m\) and \(P_y^m\) of the mouth are determined by substituting the calculated values of \(\Delta Y\), \(\Delta X\) and \(P_z^m\) into (5.7).

5.4. Update of the face model’s position and size

After the new 3D center positions of the eyes and the mouth of the face model Candide have been determined, the face model is scaled and shifted according to Eq. (2.1). Here, the result \(P^{s(0)}\) of Eq. (2.1) is the result \(P^{s(0)}\) of this step.

6. Estimation of the 3D eye center positions along the view lines and update of the face model’s orientation

In Section 5, the face model Candide was updated in the eye–mouth plane to match the location of the person’s face. Furthermore, the orientation of the face model, i.e. the norm of the eye–mouth plane, is one of the important parameters of the 3D model head shape. Thus, updating the face model’s orientation during the sequence will improve the accuracy of face tracking. This problem is addressed in this section.

6.1. Principle of estimation of the face model’s orientation

For the simple face model Candide as discussed in Section 2, its orientation is determined only by the 3D eye and mouth center positions in the 3D space. However, only using a monocular view of a face is not sufficient to estimate the true positions of the eyes and the mouth of the person in the 3D space. It is known that a parallel movement of the eye–mouth plane in the 3D space along the view lines of the eyes and the mouth does not change the face model’s orientation. Hence, having those true positions is not a necessary condition to determine the face model’s orientation. One of three positions, either eye or mouth, can be fixed during updating the face model’s orientation. Here, such a strategy that the mouth center position is fixed and the eye
center positions along their view lines have to be estimated is exploited to update the face model's orientation.

Estimation of the face model's orientation minimizes the mean square luminance differences $\Delta I$ in the facial area between the projection of the face model and the real image. The facial area is determined by the projection of the face model onto the image plane, except the eye and mouth areas. These areas are excluded due to the local motion of the eyes and the mouth. Let $I_k$ be the luminance of the frame $s_k$ and $\hat{I}_k(P''', P'''')$ the luminance of the projection [19] of the face model $\hat{s}_k(P''', P'''')$ at time instant $k$. Here, the positions $P''' = (P_x'', P_y'', P_z'')$, $P''' = (P_x''', P_y''', P_z''')$ and $P'''' = (P_x'''', P_y'''', P_z'''')$ are the left eye, right eye and mouth center points after the update of the face model's orientation. According to the second assumption in Section 5, the 3D center positions $P'''$, $P''''$ and $P'''''$ of the eyes and the mouth which are to be estimated build an isosceles triangle (Fig. 6) in the 3D space, i.e.,

$$ \langle P''' - P''' \rangle \cdot \langle P''''' - P''' \rangle = 0. \tag{6.1} $$

Therefore, estimation of the orientation of a person's face can be formulated as follows:

$$ \sum (I_k - \hat{I}_k (P''', P''''))^2 \to \text{MIN}, \tag{6.2} $$

with the three conditions, Eq. (6.1),

$$ P''''' = P'''', \tag{6.3} $$

and

$$ P''', P'''' \in \mathbb{R}^3. \tag{6.4} $$

Condition (6.3) means that the mouth of the face model stays in the same position during updating the face model's orientation.

6.2. Estimation of the 3D eye center positions along the view lines

Estimation of the 3D eye center positions $(P''', P'''')$ of the face model minimizes the mean square luminance difference between the projection of the face model $\hat{s}_k(P''', P'''')$ and the real image $s_k$. It is assumed that objects have diffusely reflecting surfaces. Furthermore, diffuse illumination of the scene is assumed. Hence, color parameters are temporarily constant. With an observation point [19] $O_k'''' = (P_k''''', P_k''''', I_k''''')$ at time instant $k$ projected onto the image plane at $p_k''''$ and the same observation point after the update of the face model's orientation $O_k''' = (P_k'''', P_k'''', I_k'''')$ projected onto $p_k'''$, the luminance difference $\Delta I''''$ between the projection of the face model $\hat{s}_k$ and the real image $s_k$ at position $p_k'''$ is then related to both eye coordinates by

$$ \Delta I'''' = s_k(p_k'''') - \hat{s}_k(p_k'''') = (g_{x}'''', g_{y}'''')^T (p_k''''' - p_k''''). \tag{6.5} $$

Substituting image coordinates by model world coordinates with a perspective projection of a pin-hole camera yields

$$ \Delta I'''' = F g_{x}'''', \frac{P_k''''}{P_k''''} - \frac{P_k''''}{P_k''''} F g_{y}'''', \frac{P_k''''}{P_k''''} \tag{6.6} $$

The position $p_k'''$ of the observation point $O_k'''$ is known. Relating $P_k'''$ to $P_k'''$ by means of Eq. (2.1), a non-linear equation with the known parameters $\Delta I''''$, $g_{x}'''$ and $F$ and two unknown $z$-coordinates of both eyes $(P_{z}'''', P_{z}'''')$ results. Let $(\Delta P_z', \Delta P_z')$ be the alterations of $z$-coordinates of both eyes. For sufficiently small alterations $(\Delta P_z', \Delta P_z')$, the linearized equation using the Taylor series expansion is

$$ \Delta I'''' = \frac{\partial \Delta I''''}{\partial P_{z}''''} \Delta P_z' + \frac{\partial \Delta I''''}{\partial P_{z}''''} \Delta P_z', \tag{6.7} $$

where

$$ \frac{\partial \Delta I''''}{\partial P_{z}''''} \bigg|_{p_{z}''''=p_{z}'''', p_{z}''''=p_{z}''''} \quad \text{and} \quad \frac{\partial \Delta I''''}{\partial P_{z}''''} \bigg|_{p_{z}''''=p_{z}'''', p_{z}''''=p_{z}''''} $$

depend on the observation point $O_k'''$ and the eye and mouth positions $(P'''', P'''', P'''')$.

Furthermore, from Eq. (6.1), there is

$$ \frac{\partial p_{z}''''}{\partial P_{z}''''} \bigg|_{p_{z}''''=p_{z}'''', p_{z}''''=p_{z}''''} =: R(P''', P'''', P''''). \tag{6.8} $$
where $R(P', P^r, P^m)$ is a coefficient only depending on the eye and mouth center positions $(P', P^r, P^m)$. For sufficiently small alterations $(\Delta P'_z, \Delta P_z)$, the alteration of z-coordinates of the right eye is equal to

$$\Delta P'_z = R(P', P^r, P^m) \Delta P_z. \quad (6.9)$$

Due to the geometric condition (6.1), both eye center positions depend on each other. According to the results of Appendix A, substituting Eq. (6.9) into Eq. (6.7), we have

$$\theta_i > \theta_r:$$

$$\Delta f^{(j)} = \left[ \frac{\partial \Delta f^{(j)}}{\partial P'_z} \right]_{P'_z = P'_z, P^r = P^r} + \left[ \frac{\partial \Delta f^{(j)}}{\partial P^r} \right]_{P'_z = P'_z, P^r = P^r} R(P', P^r, P^m) \Delta P'_z, \quad (6.10)$$

$$\theta_i < \theta^r \text{ or } \theta_i = \theta_r:$$

$$\Delta f^{(j)} = \left[ \frac{1}{R(P', P^r, P^m)} \frac{\partial \Delta f^{(j)}}{\partial P^r} \right]_{P'_z = P'_z, P^r = P^r} + \left[ \frac{\partial \Delta f^{(j)}}{\partial P'_z} \right]_{P'_z = P'_z, P^r = P^r} \Delta P'_z \quad (6.11)$$

where the two symbols $\theta_i$ and $\theta_r$ are defined in Fig. 8 (see Appendix A).

In order to get the reliable estimate, Eq. (6.10) or Eq. (6.11) has to be established for several hundred observation points. The residuum of the equation system in the different cases is then minimized by linear regression:

$$\sum_{i,j} (\Delta f^{(j)})^2 \rightarrow \text{MIN}. \quad (6.12)$$

In order to make the estimation more robust, only observation points should be used for which the following inequation is satisfied [19]:

$$|\Delta f^{(j)}| < \sigma_i, \quad (6.13)$$

where $\sigma_i$ is the standard deviation of all residuals $\Delta f^{(j)}$ according to Eq. (6.10) or Eq. (6.11).

After that, the z-coordinate of one eye of the face model is compensated according to the different cases, i.e.,

$$\theta_i > \theta_r: \quad P'_z = P'_z - \Delta P'_z, \quad (6.14)$$

$$\theta_i < \theta^r \text{ or } \theta_i = \theta_r: \quad P'_z = P'_z - \Delta P'_z, \quad (6.15)$$

whereas the z-coordinate of the other eye is calculated based on Eq. (6.1). In general, Eq. (6.1) gives two values of the eye z-coordinate. That value with the smaller mean square luminance difference between the projection of the face model and the real image, except the eye and mouth areas, is selected as the eye z-coordinate. Then, the x- and y-coordinate of both eyes are calculated according to a perspective projection of a pinhole camera (Eqs. (5.2) and (5.3)), and the face model is moved according to Eq. (2.1). Afterwards, a new set of estimation equations is established, which give the new alterations of the eye z-coordinates. Due to the linearization, the 3D eye coordinates have to be estimated iteratively.
6.3. Update of the face model’s orientation

After the 3D eye center positions of the face model Candide along the view lines have been estimated, the face model’s orientation is updated according to Eq. (2.1). Here, the result \( P^{(0)} \) of Eq. (2.1) is the result \( P^{*{(0)}} \) of this step.

7. Experimental results

The proposed algorithm for face tracking has been tested with natural image sequences and synthetic images. The natural image sequences are Miss America and Akiyo with a spatial resolution corresponding to CIF and a frame rate of 10 Hz. For generating a synthetic image, a wireframe (Fig. 9(e)) including the face model Candide is used, which was calculated with the coder in [9] and adapted on an original frame of the sequence Miss America (Fig. 9(a)). After projection of the texture onto the wireframe, it is moved in the 3D space and a synthetic image is created by an image synthesis. In the experiments with the synthetic images, the motion back to the original image has to be estimated.

7.1. Results with synthetic images

The proposed algorithm has been tested with synthetic images. The improvements of the proposed algorithm are shown with the accuracy of the estimated face model’s orientation, which is represented by the angles \( \gamma_x, \gamma_y, \gamma_z \) between the norm of the eye–mouth plane and the x-, y- and z-axis of the coordinate system, respectively.

7.1.1. Simulation for the update of the face model’s orientation

First, only a part of the proposed algorithm, the update of the face model’s orientation, is tested. The synthetic image is generated by an image synthesis after moving both eyes of the textured face model Candide along their view lines. The mean square difference of the luminance between the synthetic image and the original image is 4.584122, which originates from the change of the face model’s orientation. Table 1 shows the simulation results. Compared to global head motion compensation [9], the absolute error between the face model’s orientation in the original image and the face model’s orientation in the synthesized image is reduced from (1.937, 3.284, 2.147) to (0.173, 0.060, 0.128) by the proposed algorithm for the update of the face model’s orientation. The mean square error (MSE) of the luminance between the original image and the synthesized image after global head motion compensation [9] is 1.726257, while the MSE of the luminance between the original image and the synthesized image after the proposed algorithm for the update of the face model’s orientation is 0.008296.

7.1.2. Simulation for the whole face tracking system

Here, the complete algorithm for face tracking is tested. The synthetic image (Fig. 9(b)) is generated by an image synthesis after rotation and translation of the textured wireframe (Fig. 9(e)) in the 3D space and additional motion of the face model Candide along the eye view lines. The mean square difference of the luminance between the synthetic image and the original image is 52.035807. Table 2 shows the simulation results. Compared to face tracking by global head motion compensation only [9], the absolute error between the face model’s orientation in the original image and the face model’s orientation in the synthesized image is reduced from (2.185, 1.323, 0.201) to (0.063, 0.338, 0.232) by the proposed algorithm for face tracking. The MSE of the luminance between the original image and the synthesized image (Fig. 9(c)) after face tracking by global head motion compensation only [9] is 0.630228, while the MSE of the luminance between the original image and the synthesized image (Fig. 9(d)) after face tracking by the proposed algorithm is 0.553297.

7.2. Results with natural videophone sequences

The proposed algorithm has been combined with the image analysis of a KBASC according to [9] and tested with different image sequences. Here, results for the two sequences Miss America and Akiyo using 50 frames for each are given. The goal of the face tracking is that the projection of the face
Fig. 9. Simulation results for tracking a face: (a) original image; (b) synthetic image; (c) synthesized image after face tracking by global head motion compensation only [9]; (d) synthesized image after face tracking by the proposed algorithm; (e) a wireframe with components Candid, head and shoulders.
Table 1
Simulation results for the update of the face model’s orientation

<table>
<thead>
<tr>
<th>Orientation of the face model Candid (degree)</th>
<th>In the original image</th>
<th>In the synthetic image</th>
<th>After global head motion compensation [9] (absolute error)</th>
<th>After update of the face model’s orientation (absolute error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_x )</td>
<td>91.915</td>
<td>89.744</td>
<td>89.978 (1.937)</td>
<td>92.088 (0.173)</td>
</tr>
<tr>
<td>( \gamma_y )</td>
<td>91.044</td>
<td>95.052</td>
<td>94.328 (3.284)</td>
<td>90.984 (0.060)</td>
</tr>
<tr>
<td>( \gamma_z )</td>
<td>2.181</td>
<td>5.058</td>
<td>4.328 (2.147)</td>
<td>2.309 (0.128)</td>
</tr>
</tbody>
</table>

Table 2
Simulation results for the whole face tracking system

<table>
<thead>
<tr>
<th>Orientation of the face model Candid (degree)</th>
<th>In the original image</th>
<th>In the synthetic image</th>
<th>After face tracking by global head motion compensation [9] (absolute error)</th>
<th>After face tracking by the proposed algorithm (absolute error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_x )</td>
<td>91.915</td>
<td>88.266</td>
<td>89.730 (2.185)</td>
<td>91.978 (0.063)</td>
</tr>
<tr>
<td>( \gamma_y )</td>
<td>91.044</td>
<td>93.708</td>
<td>92.367 (1.323)</td>
<td>91.382 (0.338)</td>
</tr>
<tr>
<td>( \gamma_z )</td>
<td>2.181</td>
<td>4.094</td>
<td>2.384 (0.201)</td>
<td>2.413 (0.232)</td>
</tr>
</tbody>
</table>

model Candid onto the image plane matches the location of the real face in the scene. Because the luminance differences in the regions of the eyes and the mouth are not taken into consideration during updating the face model’s orientation, it may be that the MSE of the luminance after the update of the face model’s shape might be larger than that after global head motion compensation only, although the face tracking accuracy is improved. Hence, the criterion MSE is not suitable to measure the improvement of the face tracking algorithm. In order to evaluate the improvement with respect to the projection of the face model Candid onto the image plane, the maximum position errors for the eyes and the mouth at image frame \( k \) and their average position errors,

\[
f_{\text{max}}^{\text{eye}, k} = \max \left[ |X_{r,k} - X_{r,k}^{t}|, |Y_{r,k} - Y_{r,k}^{t}| \right],
\]

\[
f_{\text{max}}^{\text{mouth}, k} = \max \left[ |X_{m,k} - X_{m,k}^{t}|, |Y_{m,k} - Y_{m,k}^{t}| \right],
\]

are introduced, where \((X_{r,k}^{t}, Y_{r,k}^{t}), (X_{r,k}, Y_{r,k})\) and 
\((X_{m,k}^{t}, Y_{m,k}^{t}), (X_{m,k}, Y_{m,k})\) are the true image coordinates of the open eyes and the mouth at image frame \( k \) (manually determined), \((X_{r,k}, Y_{r,k}), (X_{r,k}, Y_{r,k})\) and 
\((X_{m,k}, Y_{m,k}), (X_{m,k}, Y_{m,k})\) are the coordinates of the eyes and the mouth of the face model projected onto the image plane at image frame \( k \). \( N \) is the number of images. \( N_{\text{eye}} \) is the number of images in which the eyes are open.

For the test sequence Miss America, the face model Candid is adapted after the second frame. The motion of this sequence is mainly parallel to the image plane. Figs. 10 and 11 show the maximum position errors \( f_{\text{max}}^{\text{eye}, k} \) and \( f_{\text{max}}^{\text{mouth}, k} \) over the frame \( k \), respectively. In Fig. 10, the missing data originate from the fact that the eyes in these frames
are closed and the true center coordinates cannot be obtained. Compared to face tracking by global head motion compensation only [9], the average position error for the eyes \( \tilde{f}_{\text{eye}} \) is reduced from 1.72 to 1.35 pel by updating the face model's position and size according to the steps described in Sections 4 and 5, and this error value is further reduced to 1.25 pel by additionally updating the face model’s orientation according to the step described in Section 6. Similarly, compared to face tracking...
by global head motion compensation only [9], the average position error for the mouth \( \tilde{x}_{\text{mouth}} \) is reduced from 3.35 to 2.02 pel by the steps of Sections 4 and 5 and further reduced to 1.65 pel by the step of Section 6. Fig. 12 shows the eye and mouth center positions of the face model projected onto the image plane for the frames 38–49 with face tracking by global head motion compensation only [9] and by the proposed algorithm.

Fig. 12. Eye and mouth center positions for the frames 38–49 of the test sequence *Miss America* (CIF, 10 Hz) with face tracking by (a) global head motion compensation only [9], (b) the proposed algorithm.

<table>
<thead>
<tr>
<th>Maximum position error (pel)</th>
<th>( \tilde{x}_{\text{eye},k}^{\max} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>( \tilde{x}_{\text{eye}} = 2.93 \text{ pel} )</td>
</tr>
<tr>
<td>b</td>
<td>( \tilde{x}_{\text{eye}} = 1.14 \text{ pel} )</td>
</tr>
</tbody>
</table>

Fig. 13. Maximum position error of both eyes for the test sequence *Akiyo* (CIF, 10 Hz), the face model is adapted after the seventh frame. (a) Face tracking by global head motion compensation only [9]. The average eye position error is 2.93 pel. (b) Face tracking by the proposed algorithm. The average eye position error is 1.14 pel.
Fig. 14. Maximum position error of the mouth for the test sequence Akiko (CIF, 10 Hz), the face model is adapted after the seventh frame. (a) Face tracking by global head motion compensation only [9]. The average mouth position error is 4.23 pel. (b) Face tracking by the proposed algorithm. The average mouth position error is 1.91 pel.

Fig. 15. Eye and mouth center positions for the frames 39–50 of the test sequence Akiko (CIF, 10 Hz) with face tracking by (a) global head motion compensation only [9], (b) the proposed algorithm.
For the test sequence *Akiyo*, the face model *Candide* is adapted after the seventh frame. In this sequence, the person often looks towards the bottom and the eyes are closed in many images. Figs. 13 and 14 show the maximum position errors \( f_{\text{eye},k}^{\text{max}} \) and \( f_{\text{mouth},k}^{\text{max}} \) over the frame \( k \), respectively. In Fig. 13, the missing data originate from the fact that the eyes in these frames are closed and the true center coordinates cannot be obtained. Compared to face tracking by global head motion compensation only [9], the average position error for the eyes \( f_{\text{eye}} \) is reduced from 2.93 to 1.14 pel by the proposed face tracking algorithm and the average position error for the mouth \( f_{\text{mouth}} \) is reduced from 4.23 to 1.91 pel. Fig. 15 shows the eye and mouth center positions of the face model projected onto the image plane for the frames 39–50 with face tracking by global head motion compensation only [9] and by the proposed algorithm.

7.3. Increase of the computation complexity

In order to measure the additional complexity introduced by the proposed algorithm, the computation time is evaluated. Experimental results applying the test sequence *Miss America* with a spatial resolution corresponding to CIF and a frame rate of 10 Hz show that the computation time for the image analysis increases by about 10% compared to the image analysis scheme used in [9].

8. Conclusions

In this paper, a new algorithm for face tracking in a knowledge-based coder for videophone sequences has been presented. It combines global head motion compensation and update of the face model’s shape. Global head motion compensation gives a coarse face tracking, while the shape update is used to further improve the face tracking’s accuracy. As a first stage of this algorithm, the method of tracking a face by global head motion compensation from [9] is used. Then, template matching and feature point extraction techniques are used to estimate the 2D eye and mouth center positions of the person’s face in the image plane. By means of these estimated 2D center positions, the shape of the face model is updated during the sequence. For shape update, not only the locations of the eyes and the mouth of the face model are adapted to match the positions of the real eye and mouth in the sequence but also the orientation of the face model is updated.

In order to evaluate the face tracking accuracy for knowledge-based coding of videophone sequences, the developed algorithm was combined with the image analysis of a knowledge-based coding scheme according to [9]. Typical head-and-shoulder videophone sequences with a spatial resolution according to CIF and a frame rate of 10 Hz have been investigated. For evaluation, error criteria have been introduced which give the position errors of the eyes and the mouth averaged over a whole sequence. Compared to face tracking by global head motion compensation only [9], the proposed face tracking algorithm reduces the average position errors for the eyes and the mouth by 48% and 53%, respectively, for the used test sequences. These experimental results show that the proposed algorithm allows a more accurate tracking than by global head motion compensation only [9]. Thus, a more precise modelling of 3D objects is possible which is required for combined coding of natural and synthetic scene contents in the framework of MPEG-4 Synthetic/Natural Hybrid Coding (SNHC).

With the accurate tracking of the face, it is easier to estimate the other facial feature points or contours, e.g. the positions of the eyelids and the lips of the mouth. Furthermore, how the coding efficiency of KBASC is affected by the more accurate tracking of the face is another important issue. These topics will be investigated further.

Acknowledgements

The author wishes to thank Prof. Dr.-Ing. H.G. Musmann for encouraging this work and many helpful discussions on KBASC. Furthermore, the author thanks Dipl.-Ing. M. Kampmann for his fruitful discussions on image analysis in KBASC. This research was supported by the Deutscher Akademischer Austauschdienst (DAAD), Germany.
Appendix A

Eq. (6.1) in Section 6 is rewritten as follows:

\[
\begin{align*}
[X_x^2 + Y_y^2 + F^2] \ P_{z''}^{n''} &= -2 F (P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F) P_{z''}^{n''} \\
&= [X_x^2 + Y_y^2 + F^2] P_{z''}^{n''} - 2 F (P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F) P_{z''}^{n''}.
\end{align*}
\]  

(A.1)

It is known that the coordinates \((P_{z''}^{n''}, P_{z''}^{n''})\) must be real. If \(P_{z''}^{n''}\) is given, the coefficients of Eq. (A.1) must satisfy inequality (A.2) in order to have a real value \(P_{z''}^{n''}\) from Eq. (A.1):

\[
(X_x^2 + Y_y^2 + F^2) (X_x^2 + Y_y^2 + F^2) P_{z''}^{n''} \leq -2 F (X_x^2 + Y_y^2 + F^2) \\
\times (P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F) P_{z''}^{n''} \\
+ F^2 (P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F)^2 \geq 0, 
\]  

(A.2)

i.e., \(P_{z''}^{n''}\) must satisfy inequality (A.2) so that we have a real value \(P_{z''}^{n''}\). Now, the question is how we can ensure to have a real value \(P_{z''}^{n''}\) under the condition of inequality (A.2). In order to answer this question, we consider the equality condition of (A.2), i.e.,

\[
(X_x^2 + Y_y^2 + F^2) (X_x^2 + Y_y^2 + F^2) P_{z''}^{n''} \leq -2 F (X_x^2 + Y_y^2 + F^2) \\
\times (P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F) P_{z''}^{n''} \\
+ F^2 (P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F)^2 = 0.
\]  

(A.3)

Solving Eq. (A.3) gives two values \(P_{z''}^{n''}\) and \(P_{z''}^{n''}\) \((P_{z''}^{n''} \leq P_{z''}^{n''})\). Because inequality (A.2) is a concave function, inequality (A.2) holds if \(P_{z''}^{n''} \leq P_{z''}^{n''}\) or \(P_{z''}^{n''} \geq P_{z''}^{n''}\), i.e., any values in the open interval \((P_{z''}^{n''}, P_{z''}^{n''})\) cannot be selected as \(P_{z''}^{n''}\). In this case, both eye positions of the face model along their view lines can only be located on the dark dashed lines (Fig. 16). In order to have real values \(P_{z''}^{n''}\) and \(P_{z''}^{n''}\), the coefficients of Eq. (A.3) must satisfy the following condition:

\[
F^2 (X_x^2 + Y_y^2 + F^2)^2 (P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F)^2 \\
- (X_x^2 + Y_y^2 + F^2) (X_x^2 + Y_y^2 + F^2) F^2 \\
\times (P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F)^2 \geq 0.
\]  

(A.4)

If the equality condition of (A.4) is satisfied, \(P_{z''}^{n''} = P_{z''}^{n''}\), i.e., any real value can be selected as \(P_{z''}^{n''}\). In this case, both eye positions of the face model along their view lines can be located on the dark dashed lines (Fig. 17), i.e., along the complete view lines. Inequality (A.4) can be rewritten as follows:

\[
\frac{P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F}{\sqrt{X_x^2 + Y_y^2 + F^2}} \geq \frac{P_x^{m} X_x + P_y^{m} Y_y + P_z^{m} F}{\sqrt{X_x^2 + Y_y^2 + F^2}}.
\]  

(A.5)

In order to simplify expression (A.5), let vectors \(V_x, V_y\) and \(P^{m}\) be the points \((X_x, Y_y, F), (X_x, Y_y, F)\).

Fig. 16. Possible center positions of the eyes located on the dark dashed lines for \(\theta_t = \theta_s\). \(OP^{m}\): view line of the right eye; \(OP^{m}\): view line of the left eye; \(OP^{m}\): view line of the mouth.

Fig. 17. Possible center positions of the eyes located on the dark dashed lines for \(\theta_t = \theta_s\). \(OP^{m}\): view line of the right eye; \(OP^{m}\): view line of the left eye; \(OP^{m}\): view line of the mouth.
and \((P^m_x, P^m_y, P^m_z)\) in the 3D coordinate system (Fig. 8), respectively. With these vectors, we have

\[
\frac{|P^m V'|}{\|P^m\|\|V'\|} \geq \frac{|P^m' V'|}{\|P^m\|\|V'\|}.
\] (A.6)

It is known that the inner product \(AB\) of two vectors \(A\) and \(B\) is defined as follows:

\[
AB = \|A\| \|B\| \cos \theta,
\] (A.7)

where \(\theta\) (0 \(\leq\) \(\theta\) \(\leq\) \(\pi\)) is the angle surrounded by two vectors \(A\) and \(B\). Substituting (A.7) into inequality (A.6) yields

\[
|\cos \theta_1| \geq |\cos \theta_r|,
\] (A.8)

where \(\theta_1\) is the angle between the view line of the left eye and the view line of the mouth and \(\theta_r\) the angle between the view line of the right eye and the view line of the mouth (Fig. 8). Because cosine is a monon-decreasing function in the interval \([0, \pi/2]\), we have

\[
\theta_1 \leq \theta_r,
\] (A.9)

from inequality (A.8) with \(\theta_1\) (0 \(\leq\) \(\theta_1\) \(\leq\) \(\pi/2\)) and \(\theta_r\) (0 \(\leq\) \(\theta_r\) \(\leq\) \(\pi/2\)).

In the case where \(P^m_z\) is given, it yields

\[
\theta_1 > \theta_r.
\] (A.10)

In this case, both eye positions of the face model along their view lines can only be located on the dark dashed lines (Fig. 18).

![Fig. 18. Possible center positions of the eyes located on the dark dashed lines for \(\theta_1 > \theta_r\). \(OP^{n'}\): view line of the right eye; \(OP^{n}\): view line of the left eye; \(OP^{m}\): view line of the mouth.](image)

References


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