Pattern Recognition 47 (2014) 525–534

Contents lists available at ScienceDirect

Pattern Recognition

journal homepage: www.elsevier.com/locate/pr

A central profile-based 3D face pose estimation

Deqiang Li [a,*], Witold Pedrycz [a,b,c,**]

[a] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada T6G 2V4
[b] Department of Electrical and Computer Engineering, Faculty of Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia
[c] Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland

ARTICLE INFO

Article history:
Received 11 July 2012
Received in revised form
25 July 2013
Accepted 30 July 2013
Available online 8 August 2013

Keywords:
3D face
Face pose estimation
Central profile
Nose tip

ABSTRACT

In this study, we develop a central profile-based 3D face pose estimation algorithm. The central profile is a unique curve on a 3D face surface that starts from forehead center, goes down through nose ridge, nose tip, mouth center, and ends at a chin tip. The points on the central profile are co-planar and belong to a symmetry plane that separates human face into two identical parts. The central profile is protrusive and has a certain length. Most importantly, the normal vectors of the central profile points are parallel to the symmetry plane. Based on the properties of the central profile, Hough transform is employed to determine the symmetry plane by invoking a voting procedure. An objective function is introduced in the parameter space to quantify the vote importance for face profile points and map the central profile to an accumulator cell with the maximal value. Subsequently, a nose model matching algorithm is used to detect nose tip on the central profile. A pitch angle estimation algorithm is also proposed. The pose estimation experiments completed for a synthetic 3D face model and the FRGC v2.0 3D database demonstrate the effectiveness of the proposed pose estimation algorithm. The obtained central profile detection rate is 99.9%, and the nose tip detection rate has reached 98.16% with error not larger than 10 mm.

1. Introduction

Recently, face recognition algorithms based on the 2D frontal face images have produced sound performance [1]. For instance, considering the FRGC v2.0 database [2], the HEC algorithm [3] resulted in 99% verification rate at 0.1% false alarm rate. For the FERET database, the recognition rates of the LGBP_mag+LGXP algorithm [4] on Fb, Fc, Duplicate I and Duplicate II reached 99%, 99%, 94% and 93%, respectively. However, successful recognition using 2D face recognition technology can only be achieved when using the frontal images. Its success is limited to the conditions of a controlled environment, which in most situations are unrealistic in real-world applications. In outdoor or uncontrolled environments, illumination and face pose might change rapidly that decrease the performance of 2D face recognition algorithms. Zhang et al. [5] provided a critical survey of research on image-based face recognition across pose. The existing techniques were comprehensively reviewed and discussed. They were classified into different categories according to their methodologies in handling pose variations. Their strategies, advantages/disadvantages and performances were elaborated on.

3D face recognition has been regarded as a promising approach that could help overcome or limit the negative effects of illumination and pose variation. Lu et al. [6] showed that 3D(x,y,z) face surface representation, referring to face's shape information, contains at most one depth value (z direction) from the view point to every point of face surface in the (x,y) plane. Medioni et al. [7], Lu et al. [8], and Faltemier [9] all identified 3 possible advantages of 3D face recognition over 2D face recognition. First, the shape is defined and can supposedly be acquired independently from lighting, whereas photometric appearance is not. Second, 3D data allows for face or head pose correction more easily than when involving 2D data. Third, 3D face shape seems likely to be more changeless with variations in cosmetic use, skin coloration, and similar surface reflectance factors than the 2D face appearance. Bowyer [10] stated that the current enthusiasm for 3D face is largely based on the promise of illumination invariance and view point invariance making recognition easier in 3D than it is in 2D.

Face pose estimation is a key problem in 3D or 3D+2D face recognition. There is a wealth of research reported on this issue, see [11–23]. Murphy-Chutorian et al. [11] presented an organized survey on head pose estimation and discussed the advantages and disadvantages of each approach and spanned 90 of the most innovative and characteristic papers. They classified the published head pose estimation approaches into 8 categories. They also proposed eight design criteria as guidelines for future development that are accurate, monocular, autonomous, multi-person, identity and lighting invariant, resolution independent, full range

* Corresponding author. Tel.: +1 780 6550091.
** Corresponding author at: Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada T6G 2V4.
E-mail addresses: deqiang_li@hotmail.com (D. Li), wpedrycz@ualberta.ca (W. Pedrycz).

0031-3203/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.patcog.2013.07.019

of head motion, and realized in real time. Gurbuz et al. [12] presented a stereovision based 3D head reconstruction and pose estimation. Their key novelty is the utilization of the face plane together with the eye location on the reconstructed face data to produce a robust head pose estimation. Perakis et al. [13] presented a novel method for 3D landmark detection and pose estimation. The method utilized 3D local shape descriptors to extract candidate interest points that are identified and labeled as anatomical landmarks. The method was evaluated using an extensive 3D facial database and achieved high accuracy even in challenging scenarios. In real-time face pose estimation, Breitenstein [14] generated an average 3D face model from the mean of an eigenvalue decomposition of laser scans. The average model was rendered for many poses that are stored on the graphics card. A novel 3D shape signature was computed for real time 3D face. Fanelli et al. [15] formulated a real time face pose estimation as a regression problem and used random regression forests to handle large training datasets. They synthesized a great volume of annotated training data using a statistical model of human face.

Nose tip, as a prominent landmark on face, is always regarded as the origin in the local face coordinate frame. Therefore, nose tip detection is a significant step in face pose estimation. There are many references focused on the nose tip detection-based pose estimation. *Z*-heuristic (*Z* maximum) method is a simple one. It is, however, sensitive to pose variation. Peng et al. [16] proposed a training-free face profiles based nose tip detection method that includes the generation of 2D Left-and-Right Most face profile, the detection of nose tip candidates, and the identification of nose tip. Faltemier [9] proposed the Rotated Profile Signatures (RPS) method that rotates the 3D face over a 180° with interval in 5° increments, and extracts the right most “profile” points at each step. These profiles were then matched with the two predefined profile models containing nose tips. Nose tip was determined when the highest similarity score is obtained. Chang et al. [17] and Colombo et al. [18] realized the automatic nose detection using the curvature information, such as mean curvature, Gaussian curvature, principal curvatures, and shape index. Their studies showed that the shape index value of nose tip region attains values in-between 0.7 and 1.

In recent years, symmetry or profile-based face pose estimation has attracted more attention. It is known that human face exhibits an almost bilateral symmetry. There is a symmetry plane, which separates the entire face into two identical parts. Beumier et al. [19] mentioned the term of “central profile”. They looked for the maximal protrusion of the central profile and the maximal symmetry of the left and right lateral profiles. Pathangay et al. [20] also exploited the symmetric structure of the human face. They used Harris/SIFT methods to produce highly erroneous matched correspondences between the test face and its mirror image, and afterward estimated the symmetry plane. Zhang et al. [21] used a PCA+ICP technique to compute an optimized registration between the original 3D face and its mirror face, and then obtained 3D face's mirror plane, i.e., a symmetry plane. The “central profile” mentioned in [19] is also referred to a “symmetry profile”, see [20,21].

In this paper, we use the bilateral symmetry of human face and propose a face pose estimation algorithm based on the central profile. The central profile is the intersection curve between the symmetry plane and 3D face surface. It is a significant curve on the middle of face surface. It starts from a forehead center, goes down through nose ridge, nose tip and mouth center, and ends at the chin tip. The central profile is protrusive and has a certain length. Most importantly, the normal vectors of the central profile points are parallel to the symmetry plane. The originality of this study associates with a new approach to detect the symmetry plane using the properties of the central profile. We define an objective function for conducting the Hough transform in parameter space that maps face profile to an accumulator cell. The face profile corresponding to the maximal accumulator cell is regarded as the central profile. The space parameters corresponding to the maximal accumulator cell are treated as the parameters of the symmetry plane. Based on the detection of the central profile, nose tip is detected and face's pitch angle is estimated. The proposed algorithm differs from those reported curvature information [17,18,22], PCA/ICP [21,23] or symmetry/profile based face pose estimation algorithms [19,20]. It comes with a high detection rate, accurate central profile and nose tip detection results, and acceptable computational cost. In addition, it is robust to noise which is inherently present in range images.

This paper is organized as follows. In Section 2, the detailed properties of the central profile and the symmetry plane detection are elaborated. In Section 3, nose model matching based nose tip detection and face pitch angle estimation are represented. In Section 4, algorithm complexity is analyzed. In Section 5, experiments carried out for a synthetic 3D face model and the FRGC v2.0 database are reported. Finally, conclusions are drawn in Section 6.

2. Symmetry plane detection based on the central profile

3D face pose estimation can be regarded as a problem of six-parameter estimation that includes 3 angles and 3 translations. Assume a standard frontal 3D face under coordinate system XYZ and another non-frontal pose under coordinate system $X'Y'Z'$, see Fig. 1. Here α is the pitch angle around the horizontal axis X. β is the yaw angle around the vertical axis Y. γ is the roll angle around the depth axis Z. $[\Delta x, \Delta y, \Delta z]$ are the translations between the origins O and O' along the three directions.

2.1. Symmetry plane and central profile

Human face is basically a symmetrical geometric object. There is a symmetry plane that divides the entire face into two proximately identical parts, e.g., the plane Y–O–Z shown in Fig. 1(a) and the plane Y'–O'–Z' shown in Fig. 1(b). The symmetry plane intersects with face surface and forms the central profile that crosses forehead center, nose tip, middle of two eyes, and mouth center, see the white curves visualized in Fig. 1.

2.2. Properties of the symmetry plane and the central profile

The symmetry plane Y'–O'–Z' in Fig. 1(b) can be obtained from the Y–O–Z plane shown in Fig. 1(a) by rotating angle γ around the axis Z and angle β around the axis Y, and translating ρ from the origin O. Namely, the symmetry plane of a non-frontal 3D face is obtained from a frontal 3D face by setting up suitable values of 3 parameters $[\gamma, \beta, \rho]$, refer to Fig. 2. Without loss of generality, we use a cutting plane to ‘cut’ face surface and generate a face profile on a face surface. It can be seen that the central profile is a special face profile and the cutting plane generating the central profile is the symmetry plane.

In Fig. 2, $\vec{n} = [n(1), n(2), n(3)]$ is the unit normal vector of a cutting plane; $\vec{p}_i$ is the unit normal vector of the face profile point p_i, see the red arrowed vectors; ρ is the normal distance from the origin O to the cutting plane. We regard the cutting plane as the plane obtained from Y–O–Z in terms of γ, β and ρ.

We can identify several interesting properties of the cutting plane.

(1) Equation of the cutting plane
The equation of the cutting plane for a non-frontal face in *XYZ* frame is expressed as follows:

$$\vec{n} \bullet [x_i, y_i, z_i] + d_i = 0 \quad (1)$$