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A New Parameterised Feature-based Generic 3D Human Face Model for Emotional Bio-robots

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Abstract

To represent various human facial expressions is an essential requirement for emotional bio-robots. The human expressions can convey certain emotions for communications of human beingswith some muscles' positions and their movements. To design and develop emotional robots, it is necessary to build a generic 3D human face model. While the geometrical features of human faces are freeform surfaces with complex properties, it is the fundamental requirement for the model to have the ability of representing both primitive and freeform surfaces. This requirement makes the Non-rational Uniform B-Spline (NURBS) are suitable for 3D human face modelling. In this paper, a new parameterised feature based generic 3D human face model is proposed and implemented. Based on observation of human face anatomy, the authors define thirty-four NURBS curve features and twenty-one NURBS surface features to represent the human facial components, such as eyebrows, eyes, nose and mouth etc. These curve models and surface models can be used to simulate different facial expressions by manipulating the control points of those NURBS features. Unlike the existing individual based face modelling methods, this parameterised 3D face model also gives users the ability to usethe model imitate any face appearances. In addition the potential applications of the new proposed 3D face model are also discussed. Besides emotional bio-robots, it is believed that the proposed model can also be applied in other fields such as aesthetic plastic surgery simulation, film and computer game characters creation, and criminal investigation and prevention.

1 Introduction

Emotional bio-robots is one of the important areas of bionic robots applications. To represent human facial expressions is an essential requirement for building emotional bio-robots, because the expressions can help bio-robots to communicate with human beings emotionally. This requirement raises the demands for three dimensional (3D) human face modelling.

With the rapid development and applications of 3D modelling techniques, a lot of research have been carried out to study human faces and to build 3D face models for various applications [1-4], especially for emotional bio-robots, aesthetic surgery, crime detection and computer game etc. One intuitive approach of modelling human faces is using scanned 3D data. It is a type of active stereo vision methods. The data obtained using 3D scanners - so called "clouds" - is a complete set of 3D information including 3D coordinates, colours, and textures rather than the profile images of an object. The number of points in "clouds" varies from hundreds of thousands to millions. Based on these "clouds", different algorithms are developed to build the corresponding 3D models [5-8].

Another 3D modelling method is the triangular patches method which is a surface approximation method. Although each triangle can be expressed in a 2D plane, numerous triangles in 3D can be connected together to approximate an arbitrary surface. A famous triangular patches face model is CANDIDE[9], which uses hundreds of triangles to represent a 3D human face with several simple facial features. Since the first CANDIDE model was proposed, there are several variations have been proposed [10-12].

The third approach of modelling 3D human faces is the statistical modelbased method. The most successful statistical face model is the morphable model established by Blanz and Vetter[13]. A pixel-level 3D prototype face database was constructed to store the statistical data. A morphable face model was derived by transforming shape and texture into a vector space representation. Later, other researchers proposed various modelling methods based on 3D morphable model using collected statistical scanning data sets [14-16].

Even though there are several existing modelling methods, the gap between these methods and the requirements of emotional bio-robots applications still urges the creation of a parameterised generic 3D human face model:

- First of all, human faces is consists of a number of geometrical regions which contain different muscles under the skin. The expressions are too complicated to simulate with a single surface model because even the minor expressions involve multiple muscles. Difficulties also exist in transferring expressions of one bio-robot to another because there is no parametric representation of the face models.
- Secondly, the 3D face model required by emotional bio-robots should be capable of generating faces with arbitrary appearances through manipulating the facial features. The previous modelling methods only provide mechanisms to represent a 3D face from data points[10, 17]. They were not mainly designed for representing facial features and especially their boundary information. Another approach for 3D face modelling is for professional engineers to design the model using 3D modelling software. But the accuracy will depend on the experience of the engineers. It is not easy for an ordinary person to create a face model.
- Thirdly, sometimes, the target people cannot present for scanning, even an image of the target person is difficult to obtain in some cases. For example, the clear frontal images of terrorists are rarely circulated in ordinary circumstances. So it is not feasible to build 3D face models using existing modelling methods.

From the above discussions, it can be seen that it is necessary to develop a parameterised generic 3D face model that can be used to help the engineers design and develop emotional bio-robots even when the robots' faces are not similar to any existing human beings, because the appearances of the robots can be easily changed by morphing some facial features of the generic model.

In this paper, we propose and implement a parameterised feature based generic 3D human face model for emotional bio-robots using Non-Uniform Rational B-Spline (NURBS). The new 3D human face model consists of 21 NURBS surface features and 34 NURBS curve features. By comparing with existing modelling methods, the proposed face model can be used to simulate the muscle movements to express different facial expressions by manipulating the control points of defined facial features. This approach also makes it possible to generating a large amount of face models with arbitrary appearances.

2 Theories and techniques of NURBS

To represent complicated human facial expressions, the proposed model should be parameterised for flexible control purpose. NURNS, as a powerful 3D geometry computation technology, has been widely applied in 3D modelling applications. As a generalised form of Bézier[18] and B-Spline[19] method, the NURBS method is ideal for geometric design. This section will discuss these useful characteristics of NURBS curve and NURBS surface.

NURBS curve is a generalised B-Spline curve. The degree of the B-Spline curve is independent of the number of control points. The degree $p$decides that the current point on the curve is affected by how many control points. The *i*-th basis of the B-Spline curve with p degree defined in knot span $[u_i, u_{i+1})$ is[20]:

$$
\begin{aligned}
&\boldsymbol{N}_{i,0}(u) = \begin{cases} 1\,, if\ u_i \le u < u_{i+1} \\ 0 \qquad , otherwise \end{cases} \\
&\boldsymbol{N}_{i,p}(u) = \frac{u - u_i}{u_{i+p} - u_i}\boldsymbol{N}_{i,p-1}(u) + \frac{u_{i+p+1} - u}{u_{i+p+1} - u_{i+1}}\boldsymbol{N}_{i+1,p-1}(u) \\
&Note{:}\frac{0}{0} = 0\,.
\end{aligned}
\tag{1}
$$

Eq. (1) is called de Boor-Cox basis function. As demonstrated in Fig. 1, the B-Spline basis function with zero degree is a step function that is only non-zero in certain knot spans. Then higher degree basis functions are computed using the de Boor-Cox basis function. Although the degree is zero, the basis functions are only non-zero in one knot span; when the degree is one, the basis functions are non-zero in two knot spans. This property can be expanded to an arbitrary degree: The basis function with degree p is non-zero in p+1 knot spans, which means the corresponding control point can affect the parameters in p+1 knot spans.

The other important properties of the B-Spline basis function are also shown in Eq. (1). It can be verified that $N_{i,p}(u)$ is non-zero in range$[u_i, u_{i+p+1})$**,** which is the p+1 consecutive knot spans from $[u_i, u_{i+1})$ to$[u_{i+p}, u_{i+p+1})$. Conversely, in any knot span$[u_i, u_{i+1})$, the number of non-zero p-degree B-Spline basis functionsare at most p+1. This is called local support property which means the shape of the curve is only affected by a certain number of control points.

Based on B-Spline basis function, the NURBS curve is defined by introducing the weights to rational B-Spline polynomial basis function as:

$$
\begin{aligned}
&\boldsymbol{C}(u) = \frac{\sum_{i=0}^{n} w_i \boldsymbol{N}_{i,p}(u)\boldsymbol{P}_i}{\sum_{i=0}^{n} w_i \boldsymbol{N}_{i,p}(u)} = \sum_{i=0}^{n} \boldsymbol{R}_{i,p}(u)\boldsymbol{P}_i \\
&\boldsymbol{R}_{i,p}(u) = \frac{w_i \boldsymbol{N}_{i,p}(u)}{\sum_{i=0}^{n} w_i \boldsymbol{N}_{i,p}(u)}\ .
\end{aligned}
\tag{2}
$$

Where$\mathbf{R}_{\mathrm{i,p}}(\mathrm{u})$ $(\mathrm{i} = 0,1,\cdots,\mathrm{n})$: is the rational basis function with degree p; $\mathbf{N}_{\mathrm{i,p}}(\mathrm{u})$ is a B-Spline basis function with degree p; $\boldsymbol{P}_i(i = 0,1,\dots,n)$is the control points; $w_i$is the corresponding weights for each $\boldsymbol{P}_i$and$w_i, w_n > 0$, all other$w_i \ge 0$.

By comparing Eq. (1) and Eq. (2), the rations basis function for NURBS is quite similar as the de Boor-Cox basis function for B-Spline. By giving the knot vector, weights vector and control points, NURBS curve can be calculated according to Eq. (2).

The NURBS curve can also be extended in 3D space to generate NURBS surface. If the two dimensions are denoted by u and v, the control points along u and v are represented as a 2D array $\boldsymbol{P}_{i,j}(0 \le i \le m, 0 \le j \le n)$; the knot vector along two directions are denoted as $\boldsymbol{U} = \{u_0, u_1, \dots, u_a\}$ and $\boldsymbol{V} = \{v_0, v_1, \dots, v_b\}$. If the degree along u and v are p and q respectively, then $a = m+p+1$ and $b=n+q+1$. By providing the weights matrix $\boldsymbol{w}_{i,j}$, the NURBS surface is defined as:

$$
\boldsymbol{S}(u) = \frac{\sum_{i=0}^{m}\sum_{j=0}^{n} w_{i,j}\boldsymbol{M}_{i,j}(u)\boldsymbol{N}_{i,j}(v)\boldsymbol{P}_{i,j}}{\sum_{i=0}^{m}\sum_{j=0}^{n} w_{i,j}\boldsymbol{M}_{i,j}(u)\boldsymbol{N}_{i,j}(v)} = \sum_{i=0}^{m}\sum_{j=0}^{n} \boldsymbol{R}_{i,p,j,q}(u,v)\boldsymbol{P}_{i,j}\,.
\tag{3}
$$

Where: $\boldsymbol{R}_{i,p,j,q}(u,v)$ is the bivariant rational basis function; $w_{0,0}$,$w_{0,n}$,$w_{m,0}$,$w_{m,n}$>0, all other $w_{i,j}$ ≥0, and

$$\boldsymbol{R}_{i,p,j,q}(u,v)=\frac{w_{i,j}\boldsymbol{M}_{i,p}(u)\boldsymbol{N}_{j,q}(v)}{\sum_{s=0}^{m}\sum_{t=0}^{n}w_{i,j}\boldsymbol{M}_{s,p}(u)\boldsymbol{N}_{t,q}(v)}. \tag{4}$$

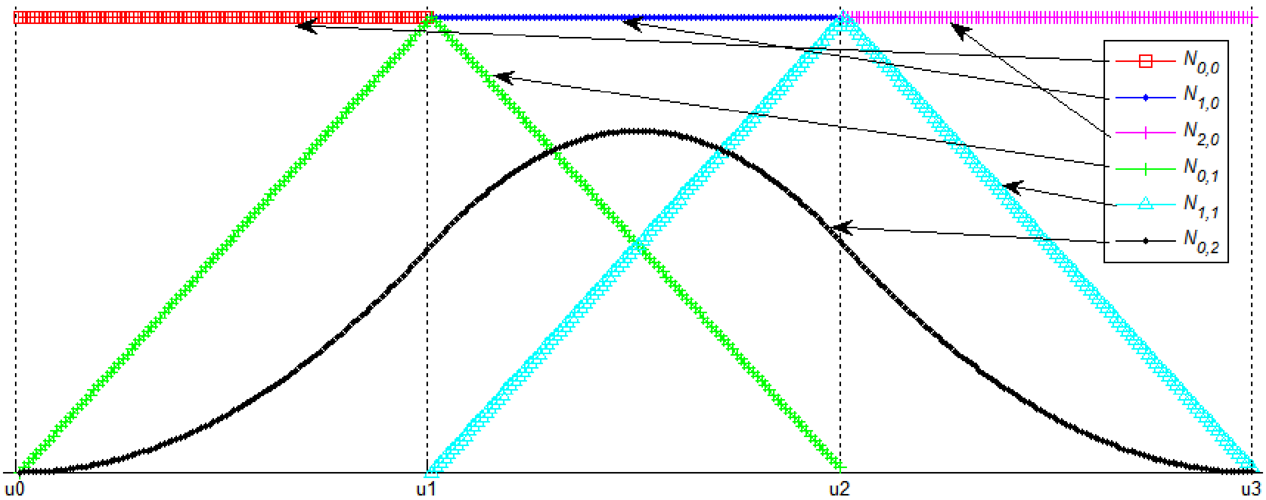

Fig. 1 B-Spline basis function $\boldsymbol{N}_{i,q}$

Fig. 2 shows two NURBS surfaces with one different weight generated according Eq. (3) and Eq. (4). It can be seen that the impact of weights on the NURBS surface: the greater the weight is, the closer the surface approaches the control point associated to the weight. Meanwhile, this affection only takes place only within certain ranges around that control point due to the local support property.

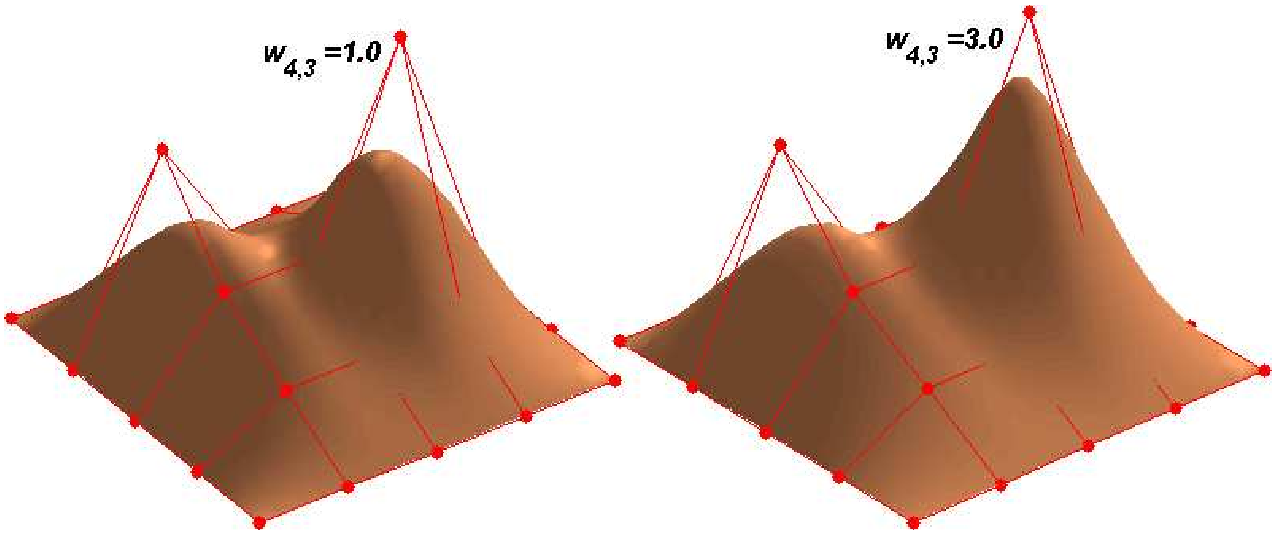

Fig. 2 Two NURBS surfaces with one different weight

3 Face model definition

To build up a parameterised generic 3D face model, a human face should be divided into a number of geometrical surfaces for the purpose of expressing the whole face with features based parameterised geometrical models. Based on the features analysis (such as nose, mouth, eyes and chin etc.) on a human face [21, 22] and the convenience and effectiveness of manipulating the generic 3D model, we've defined 34 curve features on a human face (as shown in Fig. 3). These curve features can be combined together to form 21 surface features (as shown in Fig. 4).

4 Reverse computation and 3D manipulation of facial features

As soon as all facial features are defined, all facial features need to be manipulated to change the appearances of the model and the adjacent features are connected together, which means no holes and gaps on the surface model. In practice, the degree of NURBS curve and surface is usually chosen as 3 to get the balance between control flexibility and computation complexity [23]. All weights are set to 1 initially and can be adjusted while manipulating the models. So the next step is to calculate NURBS control points and knot vectors by reverse computation.

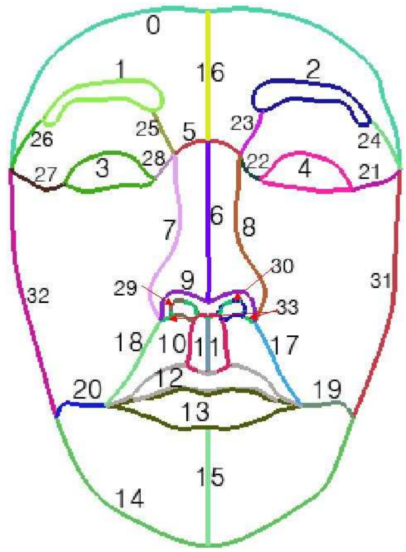

Fig. 3 Features of NURBS curve face model

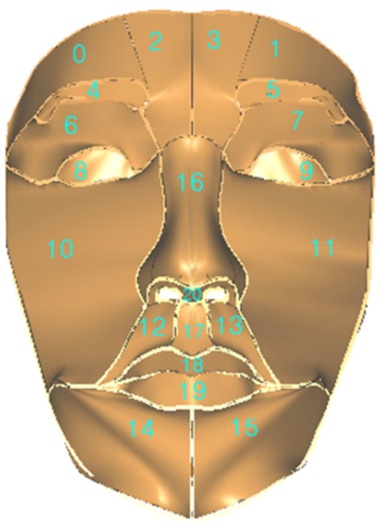

Fig. 4 Features of NURBS surface model

The problem of NURBS curve reverse computation can be described as: given a set of data points $Q = \{q_0, q_1, q_2, \ldots, q_m\}$, to compute the control points $\boldsymbol{P}_i$, weights w_i, and knot vector $\boldsymbol{U}$ with a specified degree p which starts from q_0 ends with q_m, and passes through q_2 to q_{m-1}. The problem of NURBS surface reverse computation is similar except it is described in a 3D space.

Assume $\boldsymbol{U} = \{u_0, u_1, u_2, \ldots, u_{n+1}, u_{n+2}, \ldots, u_{n+p}, u_{n+p+1}\}$ is the knot vector of target NURBS curve, because the NURBS curve passes through the first and last control points, such condition for knots holds: $u_0 = u_1 = u_2 = \cdots = u_p = 0$, $u_{n+1} = n_{n+2} = u_{n+3} = \cdots = u_{n+p+1} = 1$. Only the knots between u_{p+1} and u_n are unknown. Because the clamped NURBS passes through the first and last control points, these two points are set as duplicated control points in this paper. The relationship between the number of control points n and the number of data points m is n=m+2. So the total number of knots in knot vector is $n+p+1=m+2+3+1=m+6$, and the total number of control points is $n+1=m+3$. The unknown knots in the knot vector is from $u_{p+1}$to u_{m+2} (u_n) can be computed by parameterising knots for each data point q_j. As expressed in Eq. (5), the cumulativechord length method [24] is used to calculate all knots:

$$u_0 = u_1 = u_2 = u_3 = 0$$
$$u_{i+3} = u_{i+2} + \frac{|q_i - q_{i-1}|}{\sum_{i=1}^{m} |q_i - q_{i-1}|} fori = 1,2, \dots, m-1 \tag{5}$$
$$u_{m+3} = u_{m+4} = u_{m+5} = u_{m+6} = 1.$$

The target curve will pass through all m data pointq_i $(0 \le i \le m)$, which means $m+1$ equations can be obtained according to Eq. (6). But according to the analysis above, the target NURBS curve has $m+3$ control points. The target NURBS curve is tangent to the bounding polygon at the first and last control points. This introduces two boundary conditions.

$$_j = \boldsymbol{C}(u) = \sum_{j=0}^{m} \boldsymbol{N}_{j,p}(\bar{u}_j)\boldsymbol{P}_j = \sum_{j=0}^{m} \boldsymbol{N}_{j,3}(\bar{u}_j)\boldsymbol{P}_j \quad (j = 0,1,2, \dots, m) \tag{6}$$

Using these two boundary conditions and parameterised knot vector, the linear equation of ***AP***=***D***are generated as Eq. (7).

$$\begin{bmatrix} a_0 & b_0 & c_0 & \cdots & \cdots & \cdots \\ a_1 & b_1 & c_1 & \cdots & \cdots & \cdots \\ \ddots & \ddots & \ddots & \cdots & \cdots & \cdots \\ \cdots & \cdots & a_{m+1} & b_{m+1} & c_{m+1} & \cdots \\ \cdots & \cdots & a_{m+2} & b_{m+2} & c_{m+2} & \cdots \end{bmatrix} \begin{bmatrix} P_0 \\ P_1 \\ \vdots \\ P_{m+1} \\ P_{m+2} \end{bmatrix} = \begin{bmatrix} d_0 \\ d_1 \\ \vdots \\ d_{m+1} \\ d_{m+2} \end{bmatrix} \tag{7}$$

Where: d_0 and d_{m+2} are the bounding conditions at the first and last control point, $d_j = q_{j-1}$ for $j=1,2,\dots,m+1$, and a_i, b_i, c_i for $i=1,2,\dots,m+1$ are the basis functions of three degrees for each $\boldsymbol{u}_i$previously computed using the cumulative chord length function. The control points vector $\boldsymbol{P}$ can be computed by $\boldsymbol{P}=\boldsymbol{A}^{-1}\boldsymbol{D}$.

As the degree, knot vector, and control points of the NURBS curve are computed, the unique curve can be evaluated using the de Boor[20] algorithm. It can also be considered as the NURBS curve whose weights equal one. It can be changed freely by either control points or weights factors. Fig. 5 is an example of the reverse computation.

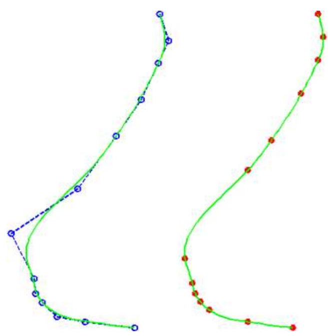

Fig. 5 NURBS curve by reverse computation
Left: calculated control points; Right: original data points

By extending the above method to 3D space, it is easy to get the NURBS surface reverse computation. Firstly, all boundaries of the target surface are computed using NURBS curve reverse computation. Next, the knot insertion is performed to make sure each pair of opposite boundaries have the same number of knots. Then, the “control net” (matrix of control points) of the target NURBS surface is determined by interpolating between each pair of control points on the opposite boundaries. Finally, the surface can be evaluated according to computed knots and control net. Fig. 6 is an example of NURBS surface reverse computation of the nose feature. By applying the reverse computation for all defined features, the NURBS surface face model can be constructed.

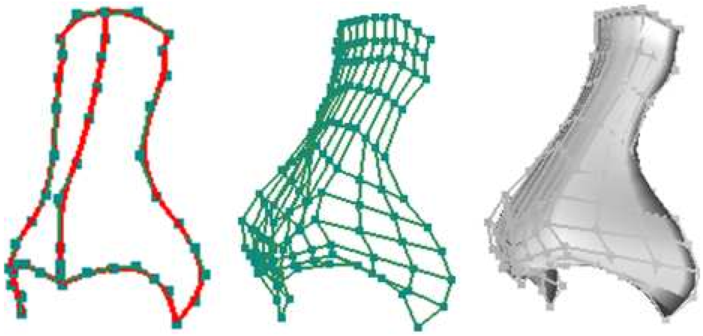

Fig. 6 Nose surface reverse computation
Left: boundary NURBS curves; Middle: computed control net; Right: evaluated NURBS surface

5 Experiment result

Based on the method introduced in Sections 2 to 4, the parameterised feature based 3D human face model is implemented in VC++.NET environment. The constructed generic 3D face models are vivid and intuitive with defined adjustable features. Fig. 7 to Fig. 11 illustrate the abilities of morphing facial features of the proposed curve and surface face models. According to the simulation, the features of the proposed models are flexible be manipulated to represent various appearances or different facial expressions.

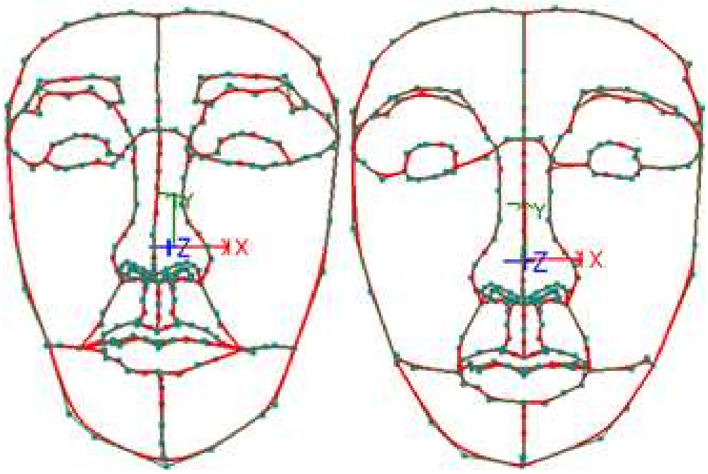

Fig. 7 Generic and morphed curve face models

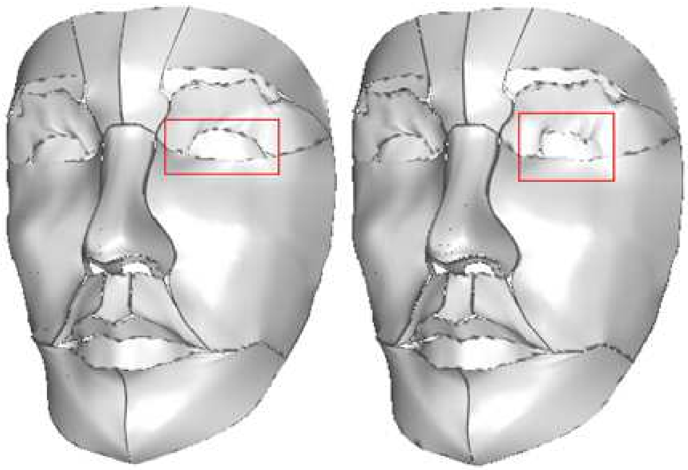

Fig. 8 Original surface models and the model with morphed left eye

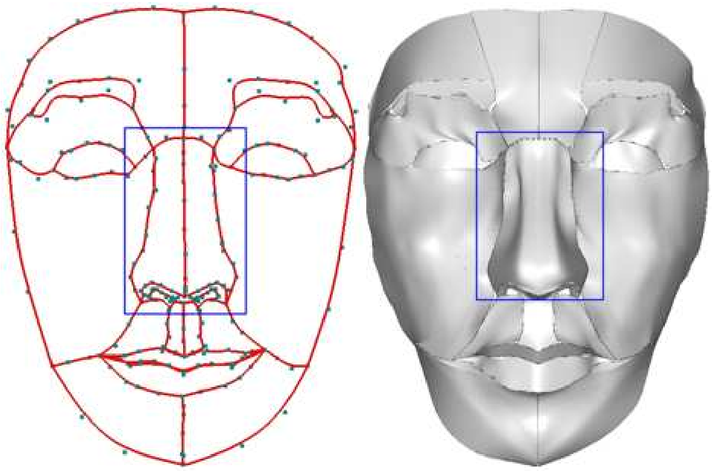

Fig. 9 Curve face model and surface face model with wider nose

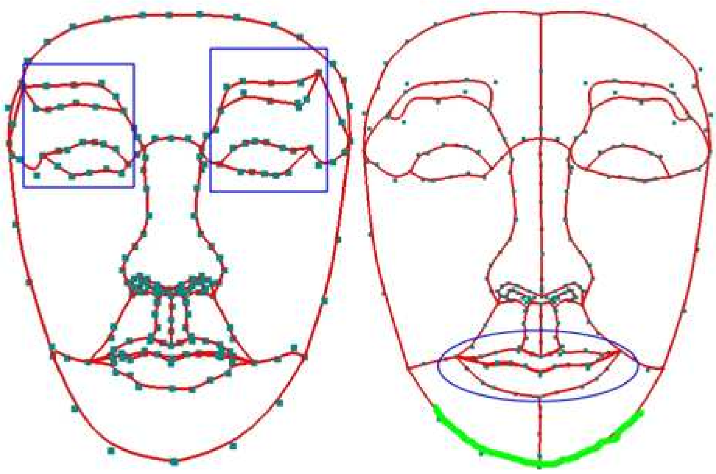

Fig. 10 Morphed NURBS curve face model
Eyes and eyebows in different shapes (left)
Smiling mouth and morphed underjaw line (right)

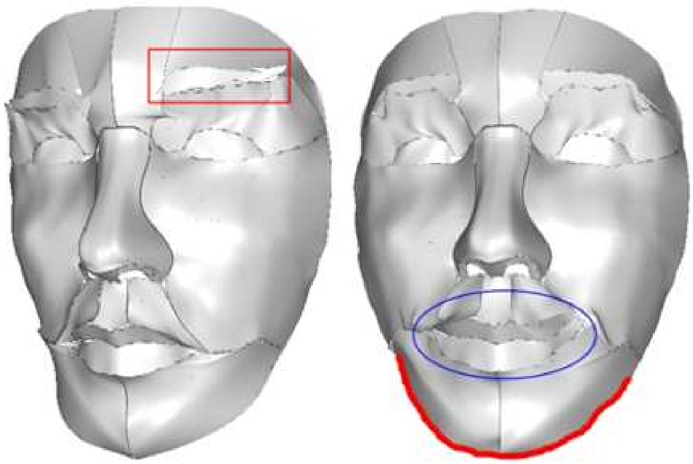

Fig. 11 Morphed NURBS surface face model
Right yebow in different shape (left)
Smiling mouth and morphed underjaw line (right)

6 Discussion of the proposed 3D face model

The method proposed in this paper can be used to build a parameterised generic 3D human face model with NURBS curves and surface features by applying reverse computation to data points. By comparing the new proposed model with existing 3D modelling methods, this parameterised face model can represent the real 3D surface of a human face mathematically to provide flexible control over all facial features. The feature based approach is very useful to perform manipulating over all defined facial features to represent various facial expressions. By combining with face detection method [25], it is possible to generate the 3D face model from images of a person automatically, which is potential to be applied in the field of face aesthetics surgery and crime prevention.

Conclusion

In this paper, the author proposed a new parameterised feature based generic 3D human face model for emotional bio-robots. The proposed face model consists by 21 NURBS surface features and 34 NURBS curve features. All features calculated by NURBS reverse computation can be manipulated by moving their control points to generate face models with arbitrary appearances for a specific person, or for someone that does not look like anyone else. The author also implemented the proposed face model and discuss advantages and the potential applications of the proposed 3D face model.

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