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Hybrid Integration of Euclidean and Geodesic Distance-Based RBF Interpolation for Facial Animation

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Abstract
Simulating believable facial animation is a topic of increasing interest in computer graphics and visual effects. In this paper we present a hybrid technique for the generation of facial animation based on motion capture data. After capturing a range of facial expressions defined by Facial Action Coding System (FACS), the radial basis function (RBF) is used to transfer the motion data onto two facial models, one realistic and one stylized. The calculations of the distances for the RBF technique are approached in three variants: Euclidean-based, geodesic mesh-based and hybrid-based. The last one takes the advantages of the first two approaches. In order to raise the efficiency, the calculations are aided by pre-processed distance data. The results are then evaluated in a quantitative and qualitative manner, comparing the animation outcomes with the real footage. Our findings show the efficiency of the hybrid technique when generating facial animation with motion capture.

Keywords: *Facial Animation, Motion Capture, Radial Basis Function, RBF, Euclidean distance, Geodesic distance, Hybrid integration, Facial Expression, Facial Action Coding System, FACS.*

Nomenclature

RBF	Radial Basis Function
FACS	Facial Action Coding System

1. Introduction
Facial modelling and animation for digital characters has become one of the most demanding topics in computer graphics, particularly within the context of feature films, video games and new emerging media such as virtual and augmented reality. Increasing research efforts aim at the new challenges to produce high-fidelity facial animation quality [1].

Due to the sensitivity of the human eye towards the features of the face, facial animation usually becomes the most observed feature in a character and the most prone to be subject of critique [2]. Given the high amount of subtleties that can be found in a facial expression such as wrinkles, micro expressions and complex anatomical structures underneath, the face is one of the most difficult parts of the human body to simulate properly, remaining still a very challenging task within computer graphics [3]. The face is the main element for communication and for the portrayal of emotion, and it is therefore key to recreate it in a believable manner when working within a digital framework. In relation to this, one of the main references for the analysis of facial motion is the FACS, a thorough study for the clasiffication of facial movements and the synthesis of facial expressions [4] which serves nowadays as one of the main references for animators to study the complexity of the human face.

Particularly for the case of facial animation, motion capture has been gaining popularity in the recent years. The collection of motion data varies depending on the requirements, and several techniques exist today to map the data onto a 3D model. One of the most common is the use of RBF, a robust surface deformation technique for the interpolation of surface scattered data [5]. Conventionally, RBF techniques use the Euclidean distance norm for their calculations, but other norms are found particularly useful for the case of facial animation, such as the geodesic distance norm. While the former is computationally faster, it fails in the proper deformation of areas with holes, such as the case of the mouth and the eyes. For these cases, geodesic calculations approximate better the results, at a cost of a more complex calculation algorithm [6].

In this paper we test the two approaches and propose the prototype of a hybrid algorithm that tries to combine the advantages of the two methods, preserving the quality of the animation and fastening the computations.

Figure 1 summarizes the steps of this process. First, we gather a collection of facial expressions using motion capture based on the theory of FACS. Second, the RBF algorithm is implemented to calculate the surface deformation and synthesis of expression in realistic and stylized 3D facial models, using our motion capture data. Three approaches of the RBF interpolation are proposed, depending on the norm of the distance: Euclidean-based, geodesic mesh-based and hybrid-based. Finally, the outcomes of each approach are evaluated with quantitative and qualitative methods.

The paper is organized as follows: Section 2 covers an overview of some of the most relevant work in the area of facial animation for this research. Section 3 explains the main process for the collection of motion capture data, including an overview of the framework used for the data transfer. Section 4 focuses on each of the three RBF approaches proposed in this project, starting with Euclidean, continuing with geodesic distance and finishing with the proposal of our hybrid approach. Section 5 includes the results of our quantitative and qualitative evaluations, analyzing the advantages and disadvantages of each of the approaches. Finally, Section 6 concludes this paper with some remarks and suggestions for future work.

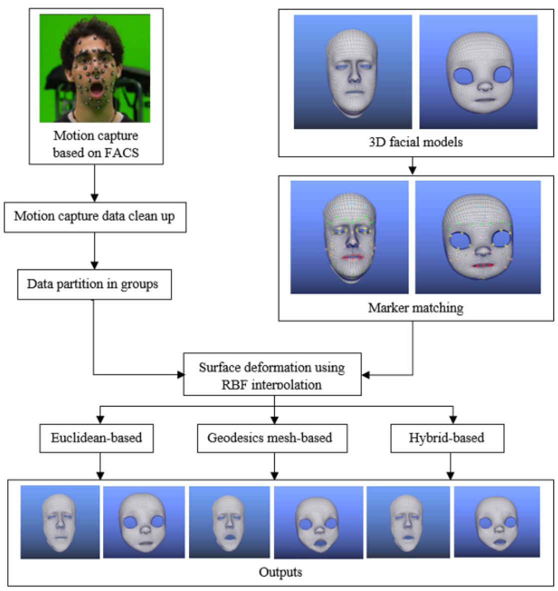

Figure 1. Framework of our work.

2. Related Work

Facial animation has been developed since the work of Parke [7] with the proposal of the first computer animation face. Nowadays, the current techniques for the recreation of facial animation have highly evolved and reached levels of high fidelity, with many different approaches developed, each of them adapting to particular requirements [2]. Remarkable examples of this can be found in the work of Alexander et. al. [8], with the photorealistic recreation of the animated face of an actor, Ichim et. al. [9] on the use of physics-based simulation for the realistic animation of facial muscles and flesh, or Cong et. al. [10], in which a muscle system was built to help in the sculpting of the facial expressions. In addition to this, facial animation has also been applied in medicine, such as the case of Sifakis et. al. [11] on the simulation of facial tissue and biomechanics on the face.

Motion capture technologies have recently gained more importance for the generation of facial animation. Taking the motion directly from the performance of real actors, the data is then transferred onto a digital model for the synthesis of facial expressions. Recent research in this area includes the work of Ruhland et. al. [12] for the synthesis of refined animation directly from motion capture data, or Zhang et. al. [13] for motion capture retargeting with topology preservation.

RBF techniques are widely used together with motion capture technology, becoming a very important tool for animation given its robustness and simplicity. Proposed first by Hardy [14], these techniques approximate the deformation of a surface given a set of control points, which define the deformation based on a particular distance function. Some of the most recent research efforts with RBF includes the work of Man-dun et. al. [15], proposing a simple RBF technique with Euclidean-based distance calculation together with the capture of face texture for the creation of realistic animation, or the work of Wan et. al. [6], who proposes an efficient RBF technique approximating the geodesic distance with discrete calculations.

The use of FACS for the development and evaluation of facial animation has become more common in recent years, such as the case of Cosker et. al. [16], who presents a method for the creation and evaluation of a scanned 3D facial model using FACS, or the work of Villagrasa and Sánchez [17], who implement an animation system based on the theory of FACS.

In this paper, we use motion capture technology and implement a hybrid-based distance approach of the RBF technique for the synthesis of facial expression, considering the theory of FACS for the acquisition of motion data and for the qualitative evaluation.

3. Motion Capture

The configuration of our motion capture system is shown in Figure 2. The set up consisted of 12 infrared cameras arranged around a circle of 5 meters of diameter, with the performer in the centre. In addition to this, an extra regular camera was set in front of the performer for recording purposes.

The performer was set with a total of 41 reflective markers, following the guidelines of the MPEG-4 standard for the description of facial motion in space [18]. Figure 3 shows the arrangement of the markers on the face.

During the session, the performer acted a selection of 24 FACS units, divided in 6 separate groups: eyebrows, eyes, nose, lips, cheeks and jaw. Table 1 shows the information of each FACS unit. Two repetitions were performed for each instance, taking the best of them for each case. After the session, the motion capture data was manually post-processed for data labelling, gap filling and clean-up.

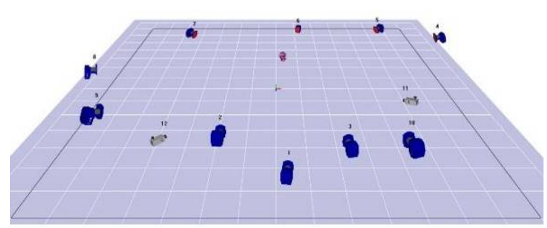

Figure 2. Motion capture set up.

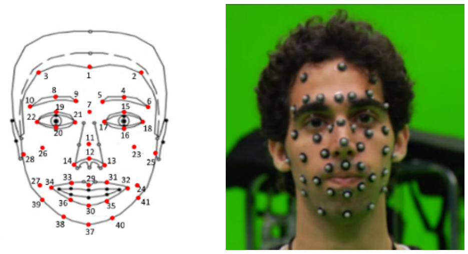

Figure 3: Markers layout (left) and arrangement on the performer's face (right).

Eyebrows	AU01 (*inner brow raiser*), AU02 (*outer brow raiser*), AU04 (*brow lowerer*)
Eyes	AU43 (*lip drop*), AU44 (*squint*), AU46 (*wink*)
Nose	AU10 (*upper lip raiser*), AU11 (*nasolabial deep*), AU39 (*nostril compressor*)
Lips	AU12 (*lip corner puller*), AU13 (*sharp lip puller*), AU14 (*dimpler*), AU15(*lip corner depressor*), AU16 (*lower lip depressor*), AU17 (*chin raiser*), AU18 (*lip pucker*)
Cheeks	AU06 (*cheek raiser*), AU33 (*cheek blow*), AU34 (*cheek puff*), AU35 (*cheek suck*)
Jaw	AU26 (*jaw drop*), AU27 (*mouth stretch*), AU29.1 (*jaw thrust front*), AU29.2 (*jaw thrust back*), AU30.1 (*jaw to the right*), AU30.2 (*jaw to the left*)

Table 1: Selection of FACS units for our experiments.

4. Facial Animation

Two generic humanoid 3D models were used to transfer the motion capture data, one realistic and another stylized. The topology of both models was cut to the limits of the facial features, hiding the ears and the back of the head, resulting in a total of 2,746 vertices for the realistic model and a total of 3,774 vertices for the stylized one. Figure 4 shows each of these models with the motion capture markers attached to them.

After matching the markers with the motion capture data, the RBF interpolation algorithm was implemented and then executed with our three variants proposed to apply the surface deformation in the facial models.

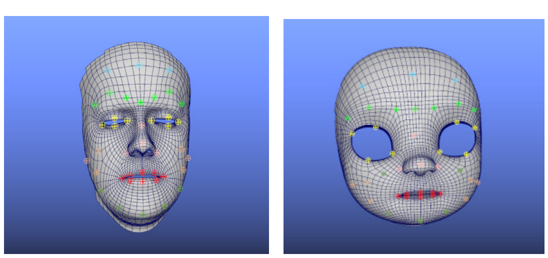

Figure 4: Realistic (left) and stylized (right) facial model with the markers placed on top.

4.1. RBF Interpolation Algorithm

Using the mesh of the facial models as a surface and the motion capture markers as a set of control points over it, the RBF function was defined to satisfy the displacement D_j of the control points:

$$D_j = f(m_j),\ (0 \leq M\text{-}1)) \qquad (1)$$

$$f(m_j) = \sum W_j\ \varphi(||m_j - m_k||),\ (0 \leq j,\ k \leq M\text{-}1) \qquad (2)$$

where M is the total number of control points, m_j is the coordinates of control point j and $\varphi(||m_j - m_k||)$ is the Gaussian RBF function described by Equation (3) below. $||m_j - m_k||$ is the norm of the distance between the two points, which we calculate with three different approaches discussed in Section 5. The weights W_j were computed with the following Equation (4) with $\gamma = 2$ in Equation (3):

$$\varphi\ (||m_j - m_k||) = e^{-||mj - mk||/\gamma} \qquad (3)$$

$$W_j = D_j / \sum \varphi(||m_j - m_k||),\ (0 \leq j,\ k \leq M\text{-}1) \qquad (4)$$

After obtaining the weights W_j with the M control points through Equation (4), the displacement Dv_i of the i^{th} vertex on a facial model with total N vertices is determined by Equation (5) below:

$$Dv_i = \sum W_j\ \varphi(||m_i - m_j||),\ (0 \leq j \leq M\text{-}1),\ (0 \leq i \leq N\text{-}1) \qquad (5)$$

4.2. Distance Matrices

To avoid redundant calculations for each of the iterations of the RBF interpolation, the distances between each vertex and each marker were pre-calculated prior running the RBF algorithm and stored in a distance matrix. The use of this allowed for more flexibility and significantly fastened the computations. Three distance matrices were used: Euclidean matrix, Geodesic mesh-based matrix, and Hybrid-based matrix.

5. Distance Calculation

At the core of the RBF interpolation is the distance calculation algorithm. Three different approaches were tested in our experiments: Euclidean-based, Geodesic mesh-based and a hybrid-based method integrating the previous two.

5.1. Euclidean-Based Distance

The Euclidean norm calculates the distance between two points on a straight line with the equation below:

$$||p - q||_{Euc} = \sqrt{((p_x - q_x)^2 + (p_y - q_y)^2 + (p_z - q_z)^2))} \qquad (6)$$

While being one of the simplest and fastest method to determine the RBF function, it creates artifacts in areas of the face that present holes, such as the mouth and the eyes as discussed in Section 6 below.

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5.2. Geodesic Mesh-Based Distance

Geodesic distance provides a more accurate measure of the distance between two points along a surface. There are several methods to find the geodesic path between two points on a surface. For the scope of our experiments, we developed a simple approximation to calculate the geodesic distance, based on the topology of the mesh.

In graph theory, the geodesic distance is the shortest path between two points along the edges of the graph, known as mesh-based distance. In this approach, we used one of the most common algorithm for the calculation of the shortest path based on the A-Star heuristic of Dijkstra's search algorithm [19, 20].

For each $||p-q||$ calculation, the shortest path between p and q is found using the A-Star heuristic. Being V the list of vertices that form the shortest-path, the geodesic mesh-based distance is the sum of the Euclidean distances between each pair of consecutive vertices which can be calculated with the following equation:

$$||p-q||_{Geo} = \sum ||V[a] - V[a+1]||_{Euc} \quad (0 \leq a \leq length(V)-1) \tag{7}$$

Despite being costlier, this method approximates better the facial deformation, and solves the artifacts appearing on the Euclidean-based approach, as stated previously by Wan et. al. [6].

5.3. Hybrid-Based Distance

Given that the calculation of the geodesic mesh-based distance is costlier, in this approach we limit them to the critical areas of the face, using Euclidean distance calculations for the other areas. Figure 5 shows the partitions of the realistic and stylized model in different regions where the geodesic mesh-based distances are calculated in the regions highlighted in yellow and Euclidean distances are determined in other regions.

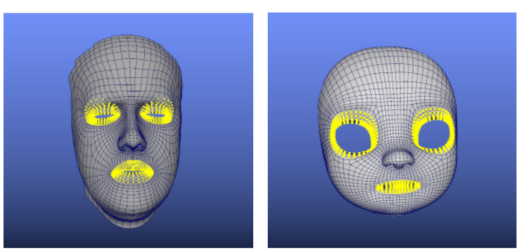


Figure 5: realistic (left) and stylized (right) facial models with the selected regions for geodesic mesh-based distance calculations and the unselected regions for Euclidean distance computations.

To avoid artifacts at the borders from the regions where geodesic mesh-based distances are calculated to those where Euclidean distances are determined, hybrid distances $||p-q||_{Hyb}$ formulated in Eq. (8) are introduced to create a smooth transition at the borders. A weight value w is used to interpolate between the geodesic mesh-based distance and the Euclidean distance, assigned in the [0.0, 1.0] range depending on the proximity to a geodesic region. The decay function used for the weight is based on a Gaussian curve with $\gamma = 2$.

$$||p-q||_{Hyb} = w\,||p-q||_{Geo} + (1-w)\,||p-q||_{Euc} \tag{8}$$

Values of w equal to 0.6 or less are marked as insignificant for geodesic calculations. For these cases, the algorithm bypasses the geodesic mesh-based calculations, fastening the computations of the hybrid distance.

Next section shows the results and the evaluation of each of these approaches in detail.

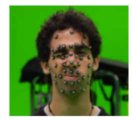
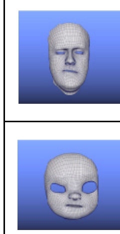
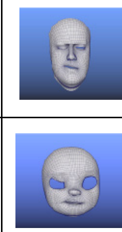
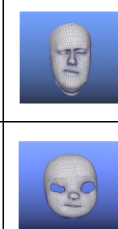
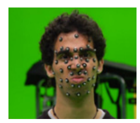
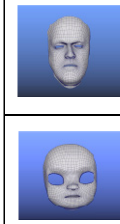
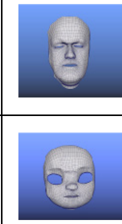
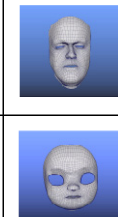
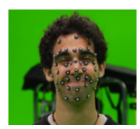
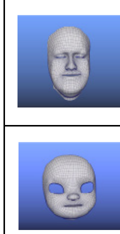
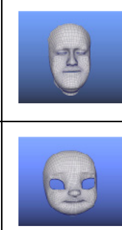
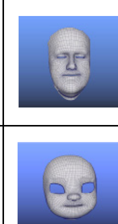
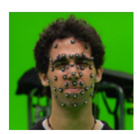
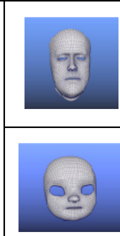
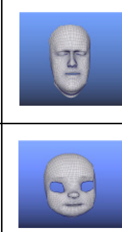
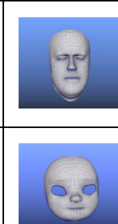
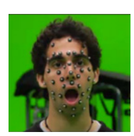
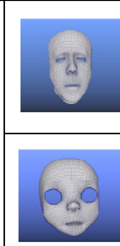
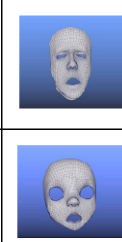
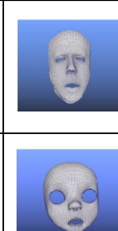
FACS unit	Euclidean	Geodesics	Hybrid
 AU46			
 AU11			
 AU06			
 AU44			
 AU27			

Table 2: Extract of some of the animation results after applying the three RBF interpolation approaches for the realistic and the stylized model. The major differences can be noticed between the Euclidean and the Geodesic approach, particularly in the areas of the mouth and the eyes.

6. Results

To compare the three different approaches for our RBF interpolation, each of the distance techniques was used to transfer the FACS-based facial movements captured onto the realistic and the stylized model described in Section 3. Table 2 shows an extract of our animation outcomes, showing the differences in surface deformation for each of the approaches.

6.1. Performance Comparison

For performance analysis, the RBF interpolation algorithms were tested on a 2.80 GHz Intel Core i7-7700HQ CPU with 16 GB RAM and a Nvidia GeForce GTX 1050Ti graphics card, executed in Autodesk Maya 2017 under a Windows 10 system.

Figures 6 and 7 show the time cost for the calculation of the RBF interpolation matrix in each approach. After these computations, the average calculation cost per vertex was 0.1 ms.

The Euclidean-based approach is the fastest one, given its simplicity. Among the other two, the hybrid-based approach reduces significantly the computation time compare to the geodesic mesh-based approach. For each case, the use of distance matrices speeds up the calculations significantly.

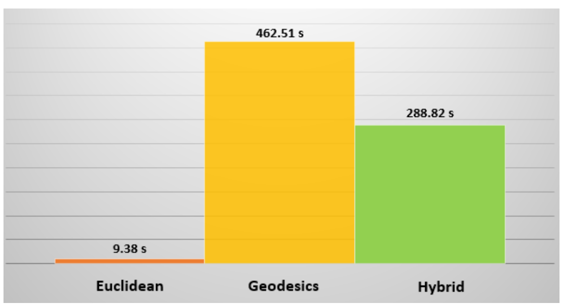


Figure 6: Computational times without distance matrices.

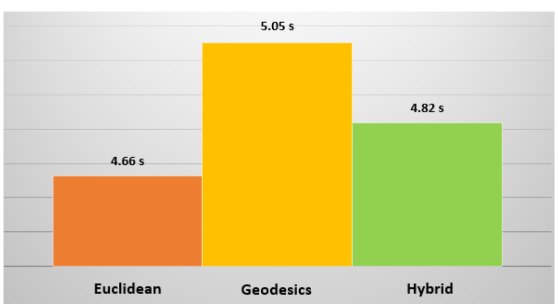


Figure 7: Computational times with distance matrices.

6.2. Quality Comparison

The animation outcomes were compared with the real footage, and a qualitative analysis was carried out observing the six groups in which we divided the face: eyebrows, eyes, nose, lips, cheeks and jaw.

The results show that the Euclidean-based approach is unsuitable for synthesis of facial expressions given the artifacts that occur in areas with holes. To avoid this, authors like Man-dun et. al. [15] propose the division of the face into separate regions, connecting the borders by interpolation.

The outcomes of the geodesic mesh-based approach show a better synthesis of facial expressions compared to the previous approach. Despite being a simple algorithm based on A-Star, the overall facial features are obtained properly, with only slightly distortions in the mesh caused by the approximation of the heuristic. More complex and efficient approximations for this problem have been proposed, such as the case of Wan et. al. [6].

Finally, the results of the hybrid-based approach show a very similar synthesis of facial expression compare to the previous approach, with proper deformation around the mouth and the eyes. In addition to this, the small artifacts appearing on the geodesic mesh-based approach are fixed by the interpolation with the Euclidean-based calculations, which results in smoother surface deformations.

Particularly for the case of the stylized model, the deformations of the eyelids do not approximate correctly the real footage, given the high density of the mesh around the eyes and the difference in proportions compared to the performer.

Overall, our outcomes show that, among the three approaches presented in this paper, the hybrid-based approach finds the best compromise between computational performance and animation fidelity.

7. Conclusions

In this paper, we presented a hybrid technique for the synthesis of facial expressions in digital characters based on motion capture data. We implemented the RBF interpolation algorithm with three distance calculation variants: Euclidean-based, geodesic mesh-based and hybrid-based, the latter taking the advantages of the two previous methods. To improve the computational time, the calculations were aided by pre-processed distance data. For our experiments, we mapped a selection of motion capture data based on FACS and performed a performance and quality evaluation for each approach. The results prove the efficiency of the hybrid technique for the synthesis of facial animation and show the significance of using distance matrix data for better performance.

Based on this research, there are potential paths for future development. The wide range of expressions generated in this research can easily lead to the creation of a detailed facial rig based on blendshapes, a solution that other authors have implemented successfully before [2]. It could also be interesting to consider the generation of facial models using techniques such as photogrammetry. In terms of evaluation, the qualitative results could be further explored with additional data and perceptual experiments to measure public perception on the animation fidelity of our methods. In addition to this, scale transfer algorithms could be applied to models that distort the human features, such as the case of the stylized face, to better approximate the expressions of the real footage. Finally, further variants can be applied for surface deformation beyond the methods presented here, such as more complex geodesic techniques, machine learning and partial-differential equations, the latter two suggested as new trending areas of research for the generation of realistic facial animation from motion capture. Further study in these areas is needed for the generation of new solutions towards high-quality realistic and believable facial animation.

8. Acknowledgements

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