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Physically Based Synthesis of Animatable Face Models

Marco Fratarcangeli

DIS - Università di Roma "La Sapienza", Rome, Italy

Abstract

We propose a physically based method to automatize the synthesis process of talking heads able to perform animation encoded in a MPEG-4 FBA stream. Starting from an input triangle mesh, we build the corresponding anatomical face model using techniques already known in literature. The novelty of our method is in using these techniques with the MPEG-4 FBA specification. The components of the anatomical model are a multi-layered soft tissue representing the facial skin, a muscle map and the underlying bony structure, including a movable jaw. Given a MPEG-4 Facial Animation Parameter expressing a basic action of the face, we use the facial model to perform this action by contracting the proper muscle group and, eventually, moving the jaw. The resulting deformed face is called morph target (MT). The whole set of morph targets is an Animatable Face Model (AFM) and we employ it to produce realistic facial animation at interactive rate.

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques - Standards I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling - Physically based modeling I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism - Animation

1. Introduction

Talking virtual characters are graphical simulations of real or imaginary persons capable of human-like behavior, most importantly talking and gesturing. They may find applications in interactive virtual environments like dialog-based interfaces or computer games.

The MPEG-4 Facial and Body Animation (FBA) standard [ISO, PF02] provides a feature-based parameterization for facial animation able to define and control the shape and the motion of a talking virtual head. Such a standard makes use of two main set of parameters: facial definition parameters (FDP), which define the shape of a face, and facial animation parameters (FAP), which control animation. The FDP set is comprised of 84 standardized feature points on the face. The FAP set provides several layers of abstraction: 6 expression and 14 viseme parameters allow high-level specification of facial expressions. 68 lower-level parameters represent elementary facial motion, providing control over eyes, tongue, mouth, head orientation, and even the nose and the ears. For each animation parameter, the assignment to the influenced feature points is specified in the standard. How movement of the feature points is in turn mapped to deformations of the skin geometry is left to the application.

In this paper, we propose a method for the automatic generation of such deformations, that we call morph targets. A morph target (MT) is a variation of the face having the same mesh topology but different vertex positions. Essentially, it is the face mesh performing a particular key movement. For each FAP, our method produces the correspondent MT performing the action expressed by the parameter. Blending together the MTs, it is possible to represent a wide range of face movements. The whole set of morph targets is called Animatable Face Model (AFM) and it is used to achieve facial animation driven by a stream of MPEG-4 FBA encoded parameters.

Our method is based on the physical simulation of the anatomical structure of the face. Input to the method are a generic static face mesh and the set of FDP, each one manually picked on the mesh itself. First, we build the anatomical model composed by a multi-layered soft skin tissue, the facial muscles and an estimated skull with a movable jaw. Then, we synthesize each morph targets acting on the proper group of muscles and, if needed, rotating the jaw. The deformation of the skin regions affected by the produced force fields is computed through a semi-implicit numerical integration scheme whose solution is the desired morph target.

The anatomy of human faces and technologies able to reproduce this anatomy on 3D meshes are already known in literature. The novelty of this paper is in the effort to employ these methods with MPEG-4 facial animation. Using an anatomical model, we produce realistic looking morph targets in an automatic and efficient manner. It is worth noting that our method is not hard-coded around a particular input face mesh and the produced talking head is compliant with the MPEG-4 FBA specification.

To test the Animatable Face Models, we used a commercial player [VT:05, Pan02]. This player gets as input the AFM and a MPEG-4 FBA encoded data stream. Each frame of the facial animation is produced by a weighted linear interpolation of the morph targets corresponding to the FAPs specified by the data stream for that animation frame. This keeps the computational cost low while the achieved animation looks realistic. Thus, such AFMs are particularly suitable for virtual environments requiring interactive facial animation of embodied agents.

The remainder of this paper is organized as follows. Sec. 2 presents related work on physically based facial animation and methods dealing with MPEG-4 FBA animation. Sec. 3 focuses on the main principles of the already know techniques to build the anatomical model and how we used them, together with MPEG-4 information, to make this process automatic. Sec. 4 describes the process to build the morph targets using the anatomical model and in Sec. 5 we provide results. Conclusions and discussions are depicted in Sec. 6.

2. Related Work

2.1. Physics-Based Approaches to Facial Animation

The creation of computer-animated human faces is a longstanding and challenging problem since the early 1970s. Key-frame interpolation technique [Par72], amongst the first techniques proposed, it is one of the most intuitive and still widely used. Basic expressions in 3D are defined at different moments in the animated sequence and intermediate frames are simply interpolated between two successive basic expressions.

The main difficulty in implementing realistic models is in the sensitivity of the human visual system to the nuances of facial expressions that it can perceive. A great deal of meaningful information is conveyed by facial skin deformation, particularly around the forehead, eyes and mouth. Physics-based approaches attempt to animate faces by simulating the influence of muscle contraction onto the skin surface. Lee, Terzopoulos and Waters [LTW93, LTW95] automatically construct a three-dimensional model of a general human face adapting a predetermined triangle mesh using the data obtained through a 3D laser scanner. Their model consists of three layers representing the muscle layer, dermis and epidermis. The elastic properties of the skin are simulated using a mass-spring system. The simulation is driven by a second-order Runge-Kutta scheme as a compromise between stability, accuracy, and speed requirements. Additional volume preservation constraints model the incompressibility of the ground substance. To this end, local restoration forces are computed to minimize any deviation in volume of the elements. An alternative integration scheme for the stiff mass-spring system is proposed by Baraff and Witkin [BW98]. They provide the theory for a stable implicit integration using very large time steps. Waters [Wat87] presented a parametric muscle model which simulate the behavior of linear and sphincter facial muscles. Another excellent anatomically based face model is provided by Kähler *et al.* [KHS01, KHYS02, Käh03]. They propose a muscle structure composed by quadric segments. Their method allows for easy creation of realistic facial models from given face geometry through their editing tool.

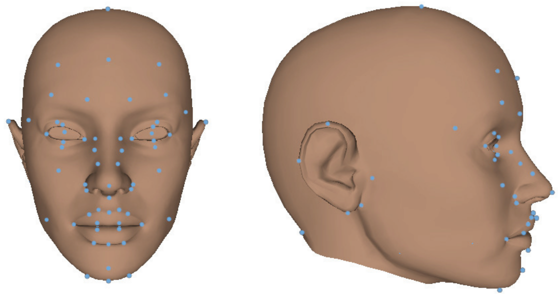

Figure 1: *Front and side view of an input face mesh with MPEG-4 FDPs scattered data set associated (cyan dots). Each FDP corresponds to a vertex of the face mesh.*

2.2. MPEG-4 FBA Compliant Talking Heads

The MPEG-4 FBA standard specifies the motion of the FDPs, leaving the rest to the particular implementations. There exists a number of techniques addressing specifically this problem. Such techniques are optimized and these automatically produce the results by using the MPEG-4 data (like FDPs). In Pandzic's approach [Pan03], deformations represented by morph targets are copied from a source talking head to a target static face. Such a "cloning" process is obtained by computing the difference of 3D vertex positions between the source morph targets and the neutral source face. This difference is then normalized and added to the vertex positions of the target face, resulting into the animatable target face. In W.S. Lee *et al.* [LESMT99], FDP set is acquired from orthogonal pictures of a real person and it is used to deform a previously built AFM and to properly fit on it the facial texture.

To our knowledge, our method is the first one delivering MPEG-4 FBA compliant talking heads through physical simulation.

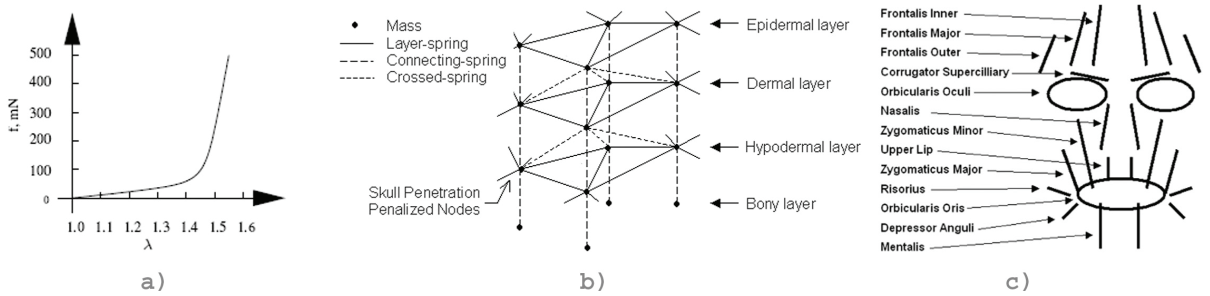

Figure 2: *a) Force f vs. uniaxial stretch ratio λ for rabbit abdominal skin. Image after [Fun93]; b) Prismatic element of the multi-layered skin tissue; c) Muscle map used in our facial model.*

3. Anatomical Face Model

Starting from a input 3D triangle mesh with MPG-4 FDPs associated (Figure 1), we use some already developed techniques to build a face model conforming to the anatomical structure of the human head. To be precise, we used the skin model and the formulation of the skull penetration constraints proposed by Lee *et al.* [LTW93, LTW95]. The muscle models have been devised by Waters [Wat87]. Fitting of the jaw bone has been introduced by Kähler *et al.* [KHS01]. The numerical integration scheme, that we use to calculate the adaptive deformation the face model, is from Baraff and Witkin [BW98]. In the following, we shortly describe these methods and how we used them together with MPEG-4 information to automatically build the anatomical face model. We specify a mechanism to place the muscle models and the jaw in the anatomically correct position by using the MPEG-4 FDPs. The influence area as well as the minimum and the maximum magnitude of contraction of the muscle and the jaw, are automatically detected for each particular input mesh.

3.1. Multi-layered Skin Tissue Model

In order to be suitable for the skin model construction, we require that the initial face mesh has to be compliant with the MPEG-4 neutral state definition [PF02].

Skin has experimentally shown to have a highly nonlinear stress-strain curve: under low stress, skin has low resistance against deformation, because the collagen fibers unroll and stretch. With stronger deformation the collagen fibers become completely stretched and aligned with the deformation, leading to a sharp increase in resistance. The resulting stress-strain curve, shown in Fig. 2a, is thus essentially biphasic. In order to simulate such a nonlinear behavior, the soft tissue representing the skin is devised as a network of masses linked together through springs. These springs modulate their stiffness according to the curve in Fig. 2a.

The geometry data of the input face mesh forms the basis for the generation of the multi-layer tissue model and defines the epidermal layer, that is the most external layer. For each triangle of the input mesh, one basic prismatic tissue element, as shown in Fig. 2b, is created by connecting the mass nodes to each other using springs. The topmost surface of the lattice represents the epidermis. It is a rather stiff layer of keratin and collagen and the spring parameters are set to make it moderately resistant to deformation. The springs in the second layer are highly deformable, reflecting the nature of dermal fatty tissue. Nodes on the third surface of the lattice represent the hypodermis to which facial muscle fibers are attached. The bottom-most surface represent the underlying bony impenetrable structure (Sec. 3.3).

To a large extent, a face mesh is formed by different parts such as teeth, hair, eyes, etc. The epidermal surface influenced by the muscles is detected by considering the face model surface where the FDP <2.1> is placed. The positions of the mass nodes on the other inner layers are computed by tracing a line from the epidermal nodes in the direction of the skin mesh center of gravity.

3.2. Facial Muscles

For facial animation, Waters [Wat87] presents a geometric muscle model which uses functions based on cone-shaped and elliptic areas to model, respectively, linear and sphincter muscles. The force exerted by the muscles is computed directly from the corresponding contraction parameter value, within the bounds prescribed by an area of influence and a fall-off function. This muscle model is computationally cheap and it is easy to implement.

A linear muscle consists of a bundle of fibers that share a common emergence point in bone and pulls in an angular direction. The end of the facial muscle attached to the skull is generally considered the origin, namely the *attachment* key point, while the other one is the *insertion* key point. The attachment is the fixed point and the insertion is where the facial muscle performs the main part of its action. A sphinc-

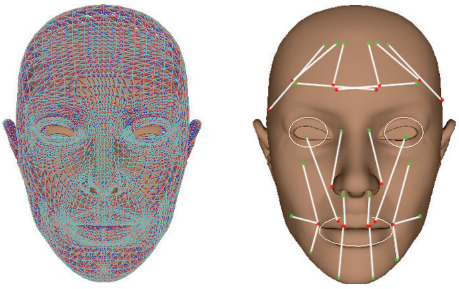

Figure 3: *Left. Multi-layered structure representing the skin. Right. The muscle map: red key points are muscle insertion points, the green ones are muscle attachment points.*

Linear Muscle		Attachment Point	Insertion Point
Frontalis	left	$11.1+\frac{1}{6}\,(11.3-11.1)$	4.1
Inner	right	$11.1+\frac{1}{6}\,(11.3-11.1)$	4.2
Frontalis	left	$11.1+\frac{1}{3}\,(11.3-11.1)$	4.3
Major	right	$11.1+\frac{1}{3}\,(11.2-11.1)$	4.4
Frontalis	left	$11.1+\frac{2}{3}\,(11.3-11.1)$	4.5
Outer	right	$11.1+\frac{2}{3}\,(11.2-11.1)$	4.6
Corrugator	left	4.3	$4.3+(4.3-4.1)$
Supercilliary	right	4.4	$4.4+(4.4-4.2)$
Nasalis	left	9.7	9.1
	right	9.6	9.2
Upper Lip	left	$9.5+\frac{1}{2}\,(9.15-9.5)$	8.10
	right	$9.4+\frac{1}{2}\,(9.15-9.4)$	8.9
Zygomaticus	left	3.9	$8.5+\frac{1}{2}\,(2.6-8.5)$
Minor	right	3.10	$8.6+\frac{1}{2}\,(2.7-8.6)$
Zygomaticus	left	5.3	8.3
Major	right	5.4	8.4
Risorius	left	5.1	8.3
	right	5.4	8.4
Depressor	left	$n=8.3+(8.3-9.1)$	8.3
Anguli	right	$m=8.4+(8.4-9.2)$	8.4
Mentalis	left	$2.1+(2.1-m)$	2.8
	right	$2.1+(2.1-n)$	2.9

Table 1: *Correspondence between MPEG-4 FDPs and* linear *muscle key points. Addictions and subtractions between FDPs are computed considering their respective position vectors. Note: n and m in the* mentalis *muscle attachment key points definition are intended to be, respectively, the* depressor anguli *attachment point left and right.*

ter muscle consists of fibers that loop around facial orifices (eyes and mouth), and has an elliptical shape.

Our face model comprises 25 independent muscles. 23 muscles have been selected taking the major functional facial muscle groups according to the muscle map model presented in the Facial Action Coding System (FACS), developed by Ekman and Friesen [EF77]. We added the remaining two muscles, namely *upper lip*. These are located between the upper lip and nose and does not exist in a real human face. They are used to increase the mobility of the mouth. Three sphincter muscles are used to represent the *orbicularis oris* and *orbicularis oculi*. The other muscles are modeled as linear ones. The complete facial muscle structure is shown in Fig. 2c.

We place the muscles in an anatomical correct position by considering the MPEG-4 FDP scattered data set. Each FDP is mapped to a proper vertex on the input face mesh. We find the correspondence between FDPs and the muscle key points according to Table 1 and 2. Once a muscle key point position is calculated, it is mapped to a mass node of the skin tissue model. We scan all the nodes in the proper skin layer and the key point is mapped to the nearest mass node. This is carried out for all the muscle key points except for the epicenter of the sphincter muscles. The position of such a key point is defined in the initialization phase and then it follows the global motion of the head (translation and rotation) during the animation.

We map the attachment key points of the linear muscles in the skull layer while the insertion key points are placed in the dermal layer. Sphincter muscle key points are mapped in the hypodermal layer. Figure 3 shows the spring network and the facial muscle map built on a test face mesh.

3.3. Skull and Jaw

A skull offset surface is estimated by scaling, according to a proper factor, the initial face mesh around its center of gravity. Such a surface permits the simulation of the impenetrability of the bony structure of the face making the skin slide on it.

Furthermore, we use some of the FDPs as a reference to estimate the shape of the lower jaw bone, that is, the movable part of the skull. Some of these reference points are linked together to estimate a sort of approximated jaw mesh. Fig. 4 shows the involved FDPs and the resulting jaw mesh.

Not all regions of the face are linked with the bones underneath. To simulate this feature, the skin nodes belonging to the area of influence of the muscles in the lips and in the cheeks are not connected to the underlying bony structure. This is achieved by setting to 0 the stiffness coefficient of the corresponding springs that connect the hypodermal layer nodes to the skull surface. Furthermore, the skull rejection force [LTW93, LTW95] is not applied to these nodes.

Sphincter Muscle		**Semi-minor axis**	**Semi-major axis**	**Epicenter**
Orbicularis	left	3.9	3.7	3.5
Oculi	right	3.10	3.12	3.6
Orbicularis Oris		$n = 8.2$	$m = 8.3$	$\frac{n+m}{2}$

Table 2: *Correspondence between FDPs and* sphincter *muscle key points.*

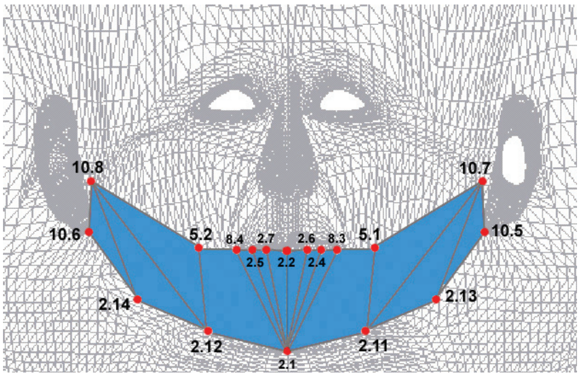

Figure 4: *Cylindrical projection of the jaw mesh estimated from the position of some MPEG-4 FDPs.*

3.4. Integration Scheme and Adaptive Simulation

Since facial muscle action is local and does not involve large portions of the face, our strategy is to adaptively use the numerical integration scheme described by Baraff and Witkin [BW98] to solve the motion equation governing the system [LTW93, LTW95] *only where needed*, that is, only in the influence area of the moving muscles and where the elastic wave significantly displaces the mass nodes.

For each facial muscle i, the skin node set $\mathbf{V}$ is divided into two subsets: the *dynamic* node set $\mathbf{V}_d^i$ and the *static* node set $\mathbf{V}_s^i$. $\mathbf{V}_d^i$ corresponds to the portions of the skin that are displaced when the facial muscle i contracts. The large number of nodes that are *not* moved during the muscle i movement are included in $\mathbf{V}_s^i$. By cutting out the evolution of these nodes, a large amount of computation resources is saved. In the initialization phase, $\mathbf{V}_d^i$ is computed automatically by considering the anatomical shape of the muscle and the skin area influenced by the muscle action. The influence area for each muscle i is obtained according to the muscle type.

For each *linear* muscle i, the central fiber length is computed as the distance between the attachment point and the insertion point. Then, we calculate the width of the muscle by multiplying its length for the *muscular width coefficient* ω, that is, a pre-calculated constant obtained observing the ratio between each real muscle width with the relative central fiber length. Each mass node in the facial skin structure is thus scanned. If the distance of the node $\mathbf{n}$ from the central fiber is less than the computed muscular width, then $\mathbf{n}$ is included in $\mathbf{V}_d^i$.

For sphincter muscles, we consider (n_x, n_y, n_z) and (epi_x, epi_y, epi_z), that is, the 3D vectors identifying the position of the mass node $\mathbf{n}$ and the sphincter muscle epicenter epi, respectively. So, $\mathbf{n}$ belongs to the muscle influence area, if it satisfies

$$\left(\frac{n_x - epi_x}{a}\right)^2 + \left(\frac{n_y - epi_y}{b}\right)^2 \leq 1 \qquad (1)$$

where a and b are the length of the semi-major axis and the semi-minor axis, respectively. Note that the gaze of the face model is in the direction of z-axis according to MPEG-4 neutral state definition, so n_x and n_y are the only interesting coordinates here.

To calculate $\mathbf{V}_d^{jaw}$ corresponding to the jaw bone, we use the approximated jaw mesh. We cast a ray starting from each skin vertex, normal to the facial surface and pointing toward the interior of the face. We test all the faces of the generalized jaw mesh with the ray for intersection. In case of positive test, the skin vertex is included in $\mathbf{V}_d^{jaw}$.

When a muscle, or the jaw, moves, there are a number of mass nodes not in the area of influence but, still, displaced to new positions due to the propagation of the elastic wave through the skin tissue. Such nodes are also inserted into the dynamic node set $\mathbf{V}_d^i$. They are detected in the preprocessing, by measuring the deformation of the skin mesh caused from the action of the muscle i. After contracting i, we apply the numerical integration to all the skin nodes. If the position of a node is modified by more than a small specified threshold, then it is considered as a node of $\mathbf{V}_d^i$, otherwise the simulation engine stops propagating the deformation further.

3.5. Auto-Calibration of the Muscle Contractions

The input face meshes can greatly differ each other for polygonal resolution, for spatial dimensions, etc. Thus, the same force field, corresponding to a given muscle contraction value, can produce very different results on the skin tissue model. Since we need to have a precise control on the face mesh to foresee the facial movements caused by the muscle contractions, we calibrate the minimal and maximal contraction value for each muscle in the preprocessing. For each linear muscle, we attach a linear spring between the key points defining its central fiber. We set the rest length of this spring to the desired length corresponding to minimal contraction force of the muscle. We incrementally increase the stiffness of this spring until it reaches the desired length. We measure the force acting on the insertion key point retrieving the minimal contraction of the linear muscle. Analogous method for the maximal magnitude. We can express the muscle contraction in percentage and we are able to know how much the muscle will deform the face.

4. Morph Targets Synthesis

Once the face model is built, we map each MPEG-4 FAP to the contractions of a muscle group. Through this mapping, for each given FAP magnitude, we are able to know precisely which vertices of the face move and how much. We use this information to build an Animatable Face Model (AFM) of the initial face mesh that can be interpreted by a MPEG-4 FBA player to perform facial animation encoded in a FAP stream.

A morph target is a variation of an object that has the same mesh topology, but different vertex positions. Essentially, it is a deformed object. Smooth morphing between a neutral object and the morph target is achieved by simple interpolation of vertex positions. Interpolation is used extensively for facial animations as mentioned in [PF02]. The use of interpolation between morph targets is preferred for its low computational requirements, ensuring good performances even on modest platforms (mobile phones, PDA). Futhermore, morph targets are intuitive and already in widespread use by animators.

We define each MPEG-4 FAP (both low- and high-level) as a morph target, that is, the initial face mesh performing the action expressed by the FAP. For each morph target, a *reference value* must be specified. For low-level FAPs, the reference value is the value of the parameter that the morph target represents. This is necessary in order to have a weight for interpolation. For visemes and expressions, the reference value is always 0. The reference value is -1 for the morph targets that are not synthesized.

Morph targets are created by modifying the muscle configuration to properly deform the face mesh. We give an example of the mapping between the low-level FAPs and the muscle contractions in Table 3. Each morph target is defined for the corresponding reference value of the FAP. We synthesized the morph targets for the set of FAP needed to perform a human facial animation. With the anatomical face model, we have not synthesized the FAPs for cartoon-style animation, like ears movements or eyeballs thrust. These can be created manually by the animators with a small effort. The tables for the mapping of the whole set of 88 MPEG-4 FAPs are available at the web site `http://www.dis.uniroma1.it/~frat/anatomic`.

No.	FAP name	Muscles	Contr.s (%)	Ref.Value
3	open_jaw	jaw	45	2048
4	lower_t_midlip	Upper lip left	150	1024
		Upper lip right	150	
		Zygomaticus minor left	10	
		Zygomaticus minor right	10	
5	raise_b_midlip	Mentalis left	150	2048
		Mentalis right	150	512
6	stretch_l_cornerlip	Risorius left	-350	512
7	stretch_r_cornerlip	Risorius right	-350	1024
8	lower_t_lip_lm	Upper lip left	150	1024
		Zygomaticus minor left	10	2048
9	lower_t_lip_rm	Upper lip right	150	2048
		Zygomaticus minor right	10	
10	raise_b_lip_lm	Mentalis left	150	2048
11	raise_b_lip_rm	Mentalis right	150	2048
12	raise_l_cornerlip	Depressor anguli left	125	2048
13	raise_r_cornerlip	Depressor anguli right	125	2048

Table 3: *Correspondence between the first eleven low-level FAPs and muscle contractions. FAP names may contain letters with the following meaning: l = left, r = right, t = top, b = bottom, i = inner, o = outer, m = middle.*

Mesh Name	vertices	faces	TB (sec.)	TAFM (sec.)
joakim	909	1752	2.344	32.376
beta	2197	4118	6.250	40.250
kevin	498	956	1.200	13.314
yoda	853	1622	2.172	30.734

Table 4: *Input face meshes specification (vertices and faces), TB: time to build the anatomical model, TAFM time to produce the anatomical face model.*

5. Results

We have performed experiments with various input meshes on a AMD PC (AthlonXP 2,14 GHz processor and 512 MB RAM). Test models differs for polygonal resolutions, shapes and topologies (both symmetric as well as asymmetric). Tab. 4 reports the time needed to build the anatomical face model and the Animatable Face Model. Fig. 5 shows some of the morph targets synthesized with our method, with the corresponding input face meshes. In particular, there are three high-level FAPs (`sadness`, `anger` and `surprise`), and three low-level parameters (`raise_bottom_midlip`, `close_left_eye` and `stretch_left_cornerlip`). Fig. 6 shows some frames from a MPEG-4 FBA encoded animation, obtained using one of our talking heads.

Experiments indicate that our method synthesizes AFMs able to perform plausible facial animation in a rather short amount of time.

6. Conclusions

We have developed a method to produce an Animatable Face Model (AFM) starting from a generic 3D face mesh with the corresponding MPEG-4 FDP scattered data set available. We used well-known techniques to reproduce an anatomical model of the input face. The facial muscles and the jaw are mapped at anatomically correct position using the MPEG-4 FDPs as reference. The face model is thus used to build the AFM. In the AFM, there are stored all the information to deform the initial face mesh and it is used to perform generic face animation encoded in a MPEG-4 FAP data stream.

It takes much less effort to produce a facial animation if, instead of working on the geometry definition level, the MPEG-4 FBA parametrization is used. Our method provides a solution to automatize the painstakingly long time process of producing the morph targets corresponding to the MPEG-4 FAPs. Animators can quickly produce a talking head and then they can easily refine the single morph targets according to their particular needs. Another beneficial effect of using MPEG-4 parameterized models is improved compressibility: a small number of parameters specifies a complete expression. By transferring only these parameters instead of a complete image or facial geometry, an animated face can be transmitted over a low bandwidth channel.

Acknowledgements

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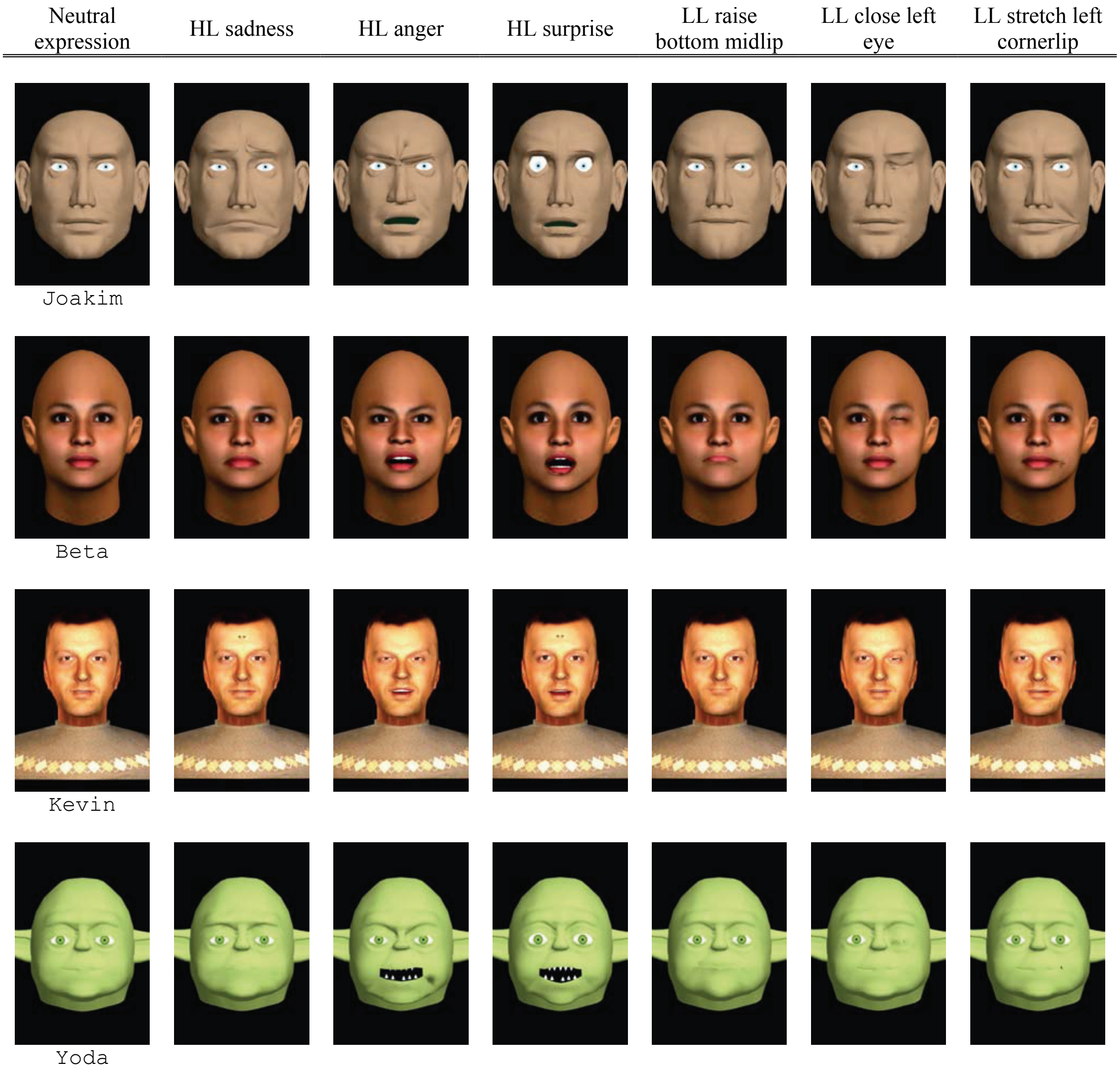

Figure 5: *Some morph targets produced with our method. The leftmost face is the input mesh, then it follows the morph targets corresponding to three high-level (HL) FAPs and three low-level (LL) FAPs.*

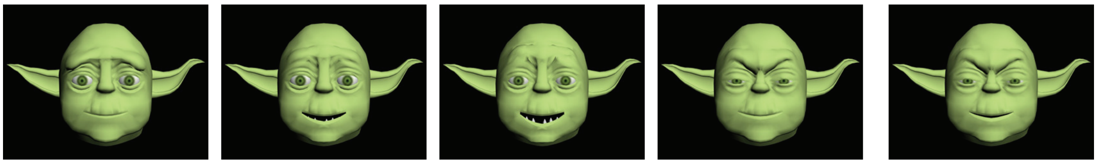

Figure 6: *Frames extracted from a MPEG-4 FBA encoded animation and performed by the talking head* `yoda`.