A Muscle Model for Animating Three-Dimensional Facial Expression

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Abstract

The development of a parameterized facial muscle process, that incorporates the use of a model to create realistic facial animation is described.

Existing methods of facial parameterization have the inherent problem of hard-wiring performable actions. The development of a muscle process that is controllable by a limited number of parameters and is non-specific to facial topology allows a richer vocabulary and a more general approach to the modelling of the primary facial expressions.

A brief discussion of facial structure is given, from which a method for a simple modelling of a muscle process that is suitable for the animation of a number of divergent facial types is described.

Cr Categories and Subject Descriptors:I.3.7 [Computer Graphics]: Three dimensional Graphics and Realism-Animation I.3.5[Computer Graphics]:Computational Geometry and Object modelling - Curve, surface, solid and object representations. I.6.4 [Computer Graphics]:Simulation and Modelling-Model Validation and Analysis

General Terms: Animation, Facial Expression.
Additional Keywords and Phrases: Minimum Set System, Digitization.

1. Introduction

There are two fundamental approaches to three-dimensional facial animation: key framing and parameterization [4][7]. Each has been exploited with varying degrees of success, but both have drawbacks. Key framing requires the complete specification of the model at each extreme, or at least the storage of the differences between facial positions [15]. Additionally, any unique subtle movement of the face must be constructed as a complete model, with the result that key framing is data-intensive and lacks specific manipulation. Parameterization avoids this problem of rigidity by grouping vertices together to preform specified tasks. However, generality is lost as soon as the process is applied to a new facial topology. Only by maintaining the same topological mesh will the parameterization hold true. Investigation by Parke [4] on the conformation of faces deals with the problem of utilizing these constraints, but it is doubtful whether the generality of such a topology will hold true over a wider range of facial types.

Facial parameterization techniques have dealt principally with the surface characteristics of the skin and have not been concerned with the motivators of the dynamics. Investigations by Badler [1] into the structural bases for the upper face dealt with the elastic nature of muscle and skin. The process is iterative in nature and deals adequately with the motivators of the actions. However, the complexities of the lower face jaw rotations render the processes unperformable. It is evident from such investigations that the motivators of the dynamic characteristics are complex, and that a simple and more general approach needs to be taken if muscle parameterization is to succeed.

This present research is concerned with the development of a more general and flexible muscle model for parameterization that will allow facial control without the requirement for hard-wiring the performable actions.

2. Motivation

The diversity of facial forms in terms of sex, age and race is enormous. It is these forms that allow us to recognize individuals and send complex non-verbal signals to one another. For the deaf and hard-of-hearing the face is a vital mode of communication, with the majority of attention placed on the observation of the lips [16][11]. As a result, a variety of models have been developed to imitate the actions of the lips [13].

Evidence from reasearch by Quentin Summerfield [17] for the deaf and hard-of-hearing has shown that real people speaking are unsatisfactory subjects for experiments into visual speech perception, because real people cannot produce specific and graded articulatory gestures. Furthermore it is evident that bi- or multi-modal emphasis in teaching the deaf lip reading should not be undervalued, as we are predisposed to relate what we hear to what we see.

Computer pre-operative surgical techniques need to determine the mobility remaining in the face after surgery. Surgical reconstruction of faces [20] uses a number of techniques to collect three-dimensional data: Moire patterning, lofting of CAT or EMR scans and lasers. The resultant data can vary enormously from one face to another, and so any resultant parameterization would, at best, be tedious to implement.

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The facial muscle process described in this paper avoids direct hard-wiring of performable actions to the data structure, and offers a simple method to determine the motional bounds of the key facial nodes.

3. Developing parameter sets for the face

Parameterization is the most desirable method of generating and controlling complex articulated models. Isolating the appropriate parameters to use for the face is perplexing but fundamental.

Inanimate objects, such as the geometric primitives, "cube, cone, sphere", can be described in terms of width, length, height, diameter, colour, weight and material, that represent basic parameters. The advantage of this approach allows concise criteria to encapsulate every member of that group or class.

Few living forms can be determined by such precise parameters. Trees [3] and other recursively generated forms seem to be the only objects belonging to such bounded sets, and consequently they can be created from a small kernel of data that is easy to produce. Unfortunately the inherent nature of the face does not allow the formation of such discrete criteria, where the terminating description of an unbounded class becomes vague and is usually discerned by the resulting visual image. The Minimum Set System [19] accepts the complexities of the unbounded class and describes the smallest number of parameters required to preform definable facial expression.

It remains very difficult to extract the necessary facial parameters from real faces. The individual facial muscles beneath the skin (and the deeper layered muscle) have not been accurately measured. Work by the nineteeth century physiologist Duchenne, applied electrical currents to freshly guillotined heads to observe the facial contortions. Later he applied the same techniques to old inmates of alms houses to create artificial expressions. In 1906 Sir Charles Bell, the anatomist, illustrated the mechanisms of the major expressions in his book *Anatomy and Physiology of Expression*, and, as he explained, a multitude of processes coalesce to produce what we instinctively recognize as an expression.

This being the case, it is still open to question as to whether there are techniques to extract the necessary facial parameters from actual faces. Investigations by Quentin Summerfield [17] into the perception of visible articulatory movements measured the face using video tape techniques. Three major problems were encountered. Firstly, an axis frame must be defined to which the measured movements may be referred. Secondly, movements of the primary articulators such as the lips and jaw must be separated from the effects of global movements. Thirdly, the measurements must be sensitive since, relative to the size of the head, significant articulatory excursions are small and seldom exceed about 25mm. Despite these inherent problems, reasonable results were obtained that describe the surface displacements of the skin.

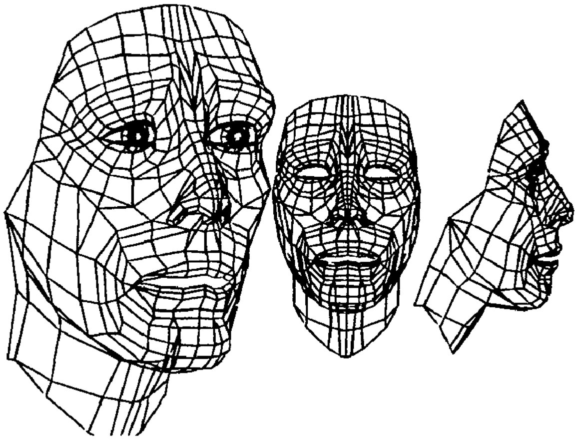


Figure 1
The Action Unit AU1 activates the inner brow raiser pulling the inner frontalis muscle. This action, with the combination of wide eyelids, pupils dilated, jaw rotated and the angular depressor pulled, displays the appearance of fear.

Significant work by Paul Ekman and Wallice Friesden, psychologists of non-verbal communication, created The Facial Action Coding System (FACS) [10], which is a notational-based environment that determines emotional states from the visible facial distortion. Individual muscles, or small groups of muscles, are described as Action Units (AU) that distort the skin tissue. This appears to be the best technique for the extraction of facial parameters useful for computer synthesis.

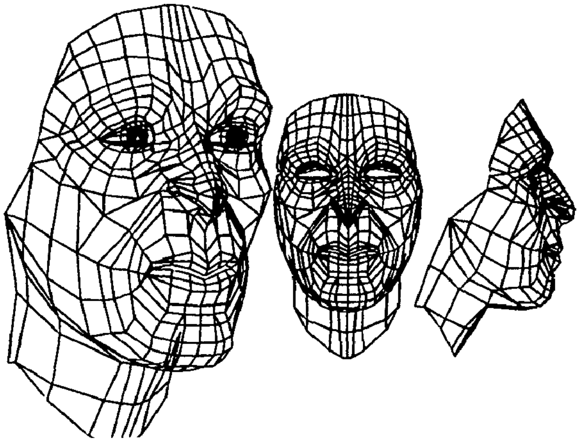


Figure 2
The Action Unit AU9 activates the Levator labii superioris alaque nasi muscle that runs from the zygomatic process to the upper lip. When it is activated the skin around the nose is pulled up dilating the nostrils and sometimes raising the upper lip.

The fifty independent facial actions can give rise to to several thousands of muscle combinations. The facial muscles can be trained, but activating them alone is not visually communicative. Six categories are described by Ekman [9]: Anger, Fear, Suprise, Disgust, Happiness and Sadness. Each of these uses multiple combinations of the Action Units. For example, one activity of the upper face in Fig 1 operates AU1, the inner brow raiser by contracting the inner frontalis muscle. In fig 2 AU9 is used, known as the 'nose wrinkler', this activates the levator labii superioris alaque nasi causing the nostrils to dilate, pulling the skin around the base of the nose up and sometimes raising the upper lip.

My own research ascribes, to individual muscles, or groups of muscles, particular parameters that remain consistant between one face and the next, in the same way that FACS is universal across a spectrum of facial types. Importantly, any contradiction between FACS and the computer parameters can easily be compared and corrected using this principle of Action Units. The goal is to model the basic facial expressions described by Ekman using FACS to validate the results.

4. The muscle and bone of the face

The cranium consists of fourteen major bones of which the manible is the only jointed structure. The mandible rotates horizontally about an axis near the ear. Inserted into the manible are the lower teeth, and the upper teeth are embeded into the maxilla process. From the front view, the teeth are the only visible bone structure, and should not be underestimated in the modelling of speech segments.

The muscles of facial expression, are subcutaneous voluntary muscles. In general they arise from the bone or facia of the head, and insert into the skin as in Fig 3. The muscle can be defined according to the orientation of the fasciculi (the individual fibres of the muscle) that may be parallel/linear, oblique or spiralized relative to the direction of pull at their attachment. There are a variety of these muscle types apparent on the face and they can be broadly divided into the upper and lower face. In the lower face there are five major groupings:

- Uppers and downers, that move the face upwards towards the brow and conversely towards the chin.

- Those that contract horizontally towards the ears and conversely towards the center line of the face.

- Oblique muscles that contract in an angular direction from the lips, upwards and outwards to the cheek bones.

- The orbitals that are circular or elliptical in nature, and run round the eyes and mouth.

- Sheet muscle, that carries out miscellaneous actions, particularly over the temporal zones, and the platysma muscle which extends downwards into the neck close beneath the skin.

The upper facial muscles are responsible for the changing appearance of the eyebrows, forehead and the upper and lower lids of the eyes (Fig 1). The muscles contract isotonically towards the static insertion into the cranium, consequently the surface tissue bunches and wrinkles perpendicularly to the direction of the muscle.

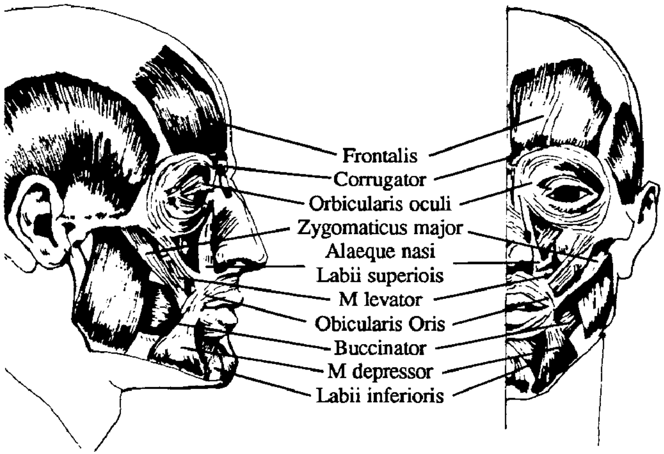


Figure 3
The major muscles of the face.

The muscles of the mouth have the most complex musclar interaction. The primary muscle being the Obicularis Oris which is a sphincter muscle with no bony attachment. Additionally the deep Buccinator muscle fibres decussate into the upper and lower lip and continue round the face to the opposite point of attachment. Three primary muscles, M Levator, Labii Superioris and Alaeque Nasi, join from above. The deeper muscles M Buccinator joins at the modiolus (the major node of the mouth) and contracts horizontally. From below, the M Depressor, Anguli Oris, M Depressor Labii Inferioris and Mentalis, all contract obliquely and vertically.

5. Factors determining the modelling of muscles

It is evident that the skin, being supported by bone and multiple layers of muscle, produces literally thousands of movement combinations. What is required is not the exact simulation of neurons, muscles and joints, but a model with a few dynamic parameters that emulate the primary characteristics. These parameters are relatively abstract, and do not attempt to model the biomechanical or neurophysiological mechanisms. Since the muscles themselves are grouped together to perform specific tasks, two broad types of muscles are considered: linear/parallel muscles that pull and sphincter muscles that squeeze. Defining the surface skin as a mesh determines that each node has a finite degree of mobility (DOM). The primary factors determining the nodal mobility are:

- Tensile strength of the muscle and skin
- Proximity to the muscle node of attachment
- Depth of tissue at the node and the proximity to the bone
- The elastic bounds of the relaxed tissue, and the interaction of other muscles.

The physical displacements of the facial nodes, especially around the mouth, have been measured by Summerfield [14] and his results indicate that displacements rarely exceed 25mm during the articulation of a/b/a sounds. Therefore assuming the node of bony attachment is static, a relationship for any intermediate node is required.

The structural-based representation suggested by Badler [1] simulates points on the skin which is distorted around an ovoid. Arcs connect points with their neighbours, so that one skin movement affects the position of its neighbour in much the same way as a network of springs. When a force F is applied to a node p the change in location is computed by:

$$p' = F/k$$

where k = sum of the spring constants at that point.

The iteration continues until a force is propagated out from the initiating point across the face. Badler's simulation is effective, but it does require specified facial models to operate upon, with tie points for the fixing of muscles to the bone and skin. This in turn requires information about length and elasticity to be determined before the iteration can begin.

With all the muscle forms it is evident that they have a highly complex three-dimensional structure endowed with viscous, elastic and other mechanical properties that result in the displacement of the skin. The simulation of such interactions would be formidible, and is not the object of this paper, however some basic issues can be established. Only a proportion of the force is effective along the line of contraction, especially as the fibres become more oblique in relation to the node of attachment. This can be determined from the length of the muscle fibre x cosine of the angle of attachment of the muscle fibres to the tendon or surface tissue [18]. This gives a general indication of the displacement of the remaining tissue. The elasticity of the skin varies with age. Young skin has a higher elasticity than older flesh and this factor too should be accommodated in the muscle model.

In addition to the static surface displacement features of the skin there are the motional characteristics. Here the requirement is to discern suitable motional criteria. Investigations by Kelso [14] into reiterant speech production outlined the dynamic properties during articulatory movement. For this process LED's were placed on the subject and monitored on an oscilloscope. Despite the inherent multi-dimensional process involved with speech, evidence showed that the system displayed near sinusoidal uniform motions, as if generated by a simple non-dissipative mass-spring system. This supports the early work of Parke [4] who produced convincing results utilizing the principle of cosine acceleration and deceleration. Subsequently this principal has been adopted as a first order approximation for this research, since the facial displacements are small and the rate at which the motions occur is extremely fast.

6. The Computer Model of muscles for the face

The research presented in this paper represents the action of muscles using the primary motivators on a non-specific deformable topology of the face. The muscle actions themselves are tested against FACS which employs action units directly to one muscle or a small group of muscles. Any differences found between real action units and those performed on the computer model are easily corrected by changing the parameters for the muscles, until reasonable results were obtained.

The muscle model was designed to be as 'naturalistic' as possible, in the representation. Two types of muscles were created: linear/parallel muscles that pull and sphincter muscles that squeeze. The key nodes of muscle attachment were measured on a number of faces, to establish the extremes of displacement and the maximum and minimum zone of influence. At best this proved to be difficult, as only the surface points could be measured, and the range of surface characteristics varies a great deal from face to face. However, it was confirmed that nodal displacements rarely exceed 25mm, the largest displacements originating from the mouth groups. The zone of influence depended upon the degree of contraction and, using FACS as a basis, it was established that the angle varied from 15 to 160 degrees, creating a convex zone. Additionally, using data from Summerfield [17], it was possible to establish degrees of freedom (DOF) for nodes around the mouth.

The fundamentals of most facial muscles determine that one end of a linear muscle has a bony attachment that remains static, while the other end is embedded in the soft tissue of the skin. When the muscle is operated, it contracts isotonically.

Looking at the concept of muscle vectors, the zone of influence in the simplest form can be viewed as circular, and the fall-off is along the radius as illustrated in Fig 4 on the three-dimensional grid. Muscle vectors can be described with direction and magnitude, both in two and three-dimensions. The direction is towards the point of attachment, and the magnitude that is zero at the point of attachment and increases to maximum at the other point of insertion into the skin.

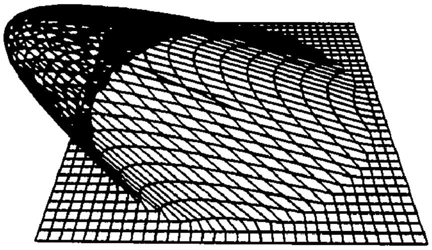


Figure 4
A muscle vector displacing a three dimensional grid with a circular cosine falloff.

The next problem is to describe how the adjacent tissue, such as the node p (Fig 5) is affected by this muscle vector contraction. At the point of attachment to the skin we can assume maximum displacement, and at the point of bony attachment zero displacement. A fall-off of the displacement is dissipated through the adjoining tissue, both across the sector Pm,Pn and V1, Ps. Using a non-linear interpolant, it is possible to represent the simple action of a muscle such as in Fig 6. Fig 5 describes the muscle vector in two dimensions. By applying the same principles to the third dimension, point p (x,y,z) is displaced p' (x',y',z').

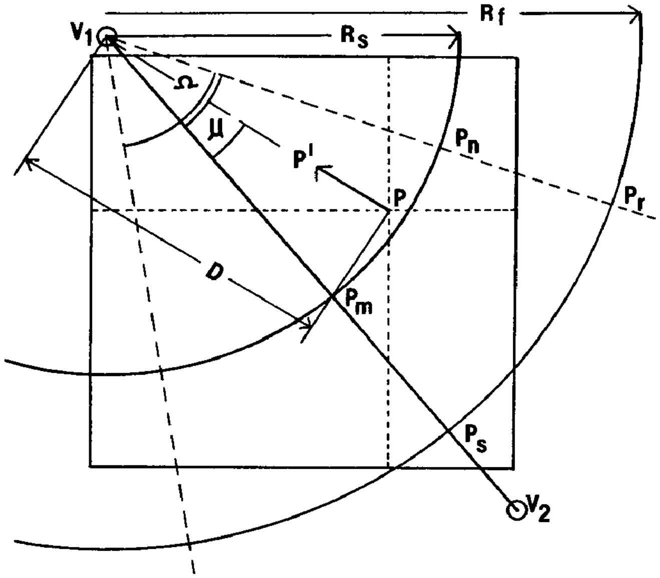


Figure 5
The muscle vector model influencing the sector V1 Pr Ps. Rs and Rf represent the fallstart fall finish of the muscle pull along the vector V1 V2.

Fig 5 V1 and V2 are two points located in two-dimensional space. Rs represents the fall-off radius start, as a real distance from V1.
Rf represents the falloff radius finish, as a real distance from V1.

Given any point P(x,y) located at a mesh node, within the zone V1 Pr Ps is displaced towards V1 along the vector P V1, this creates P' (x',y') where:

$$x' \propto f(K.A.R.x)$$
$$y' \propto f(K.A.R.y)$$

where:

K is the muscle spring constant
Ω is the maximum zone of influence
D is the vector V1 P distance

The angular displacement factor A is defined as:

$$A = \cos(\mu/\pi \, . \, \pi/2)$$

where μ is the angle between V1 V2 and V1 P
The radial displacement factor R is defined as:

$$R = \cos((1 - D/Rs)\,\pi/2)$$

for P inside V1 Pn Pm, and

$$R = \cos((D - Rs) / (Rf - Rs)\,\pi/2)$$

for P inside Pn Pr Ps Pm

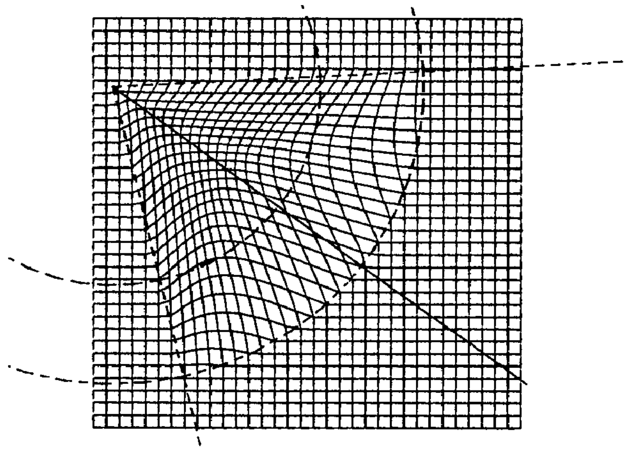


Figure 6
A three dimensional muscle vector laying in the x y plane. Zone of influence 35.0, fallstart 7.0, fallfin 14.0, muscle spring constant 0.75, elastisity 1.0.

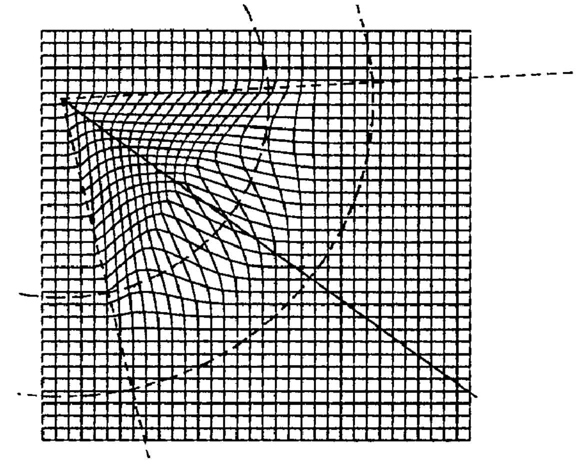


Figure 7
The same muscle vector parameters as in figure 6 but with the elasticity raised to a power 10.0.

Fig 6 illustrates the cosine interpolant, while Fig 7 shows the cosine raised to a power to decrease the elasticity of the mesh.

The sphincter muscle that squeezes the skin tissue can be described from a single point around which the surface contracts as if drawn together like a string bag. This can be described as occurring uniformly around the point of contraction, therefore the angular displacement is no longer required:

$$x' \propto f(K.R.x)$$
$$y' \propto f(K.R.y)$$

This results in the following activity in Fig 8.

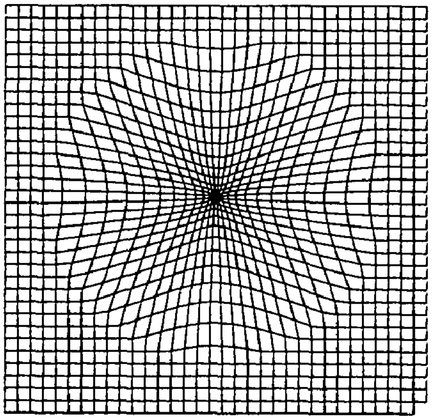


Figure 8
Sphincter muscle

Obviously muscles do not behave in such a regular fashion, therefore elliptical shapes are created that represents the shape of the oris by the addition of a longitudinal and vertical axis (Fig 9).

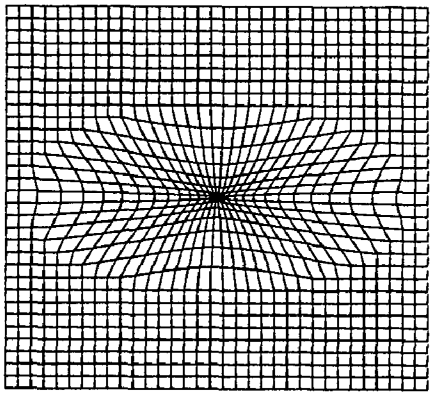


Figure 9
Eliptical sphincter muscle

The limits of a muscle action can be determined by the spring constant K, which represents the maximum displacement of the muscle. The problem associated with this model is that each muscle action is independent, and the actual nodal displacement is determined by a succession of muscle actions. This is more extreme when the contractions become isometric and nodes are shifted out of the zone of influence of adjoining muscle vectors. In this way there is a danger of exceeding the degree of freedom (DOF) of any node. The nodal structure of the face determines that each vertex has a finite DOF. By positioning the facial muscles, both feasible and impossible, and then preprocessing the structure, the DOF of each node can be determined. In this manner the order of the muscle contractions will not become isometric, as each node will store information about its common attractors (Fig 10).

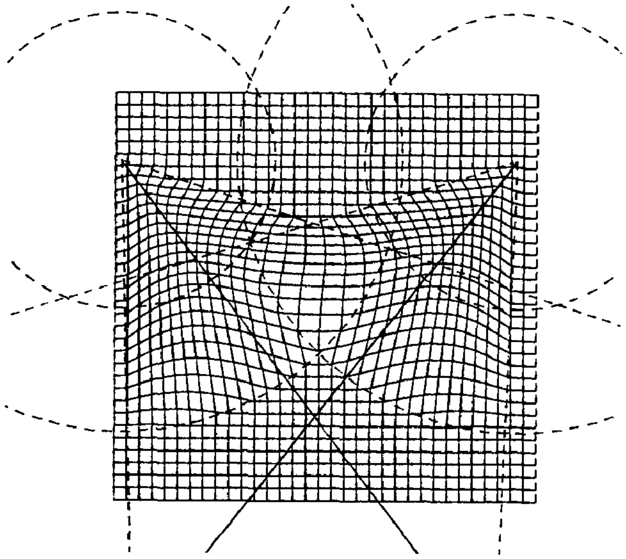
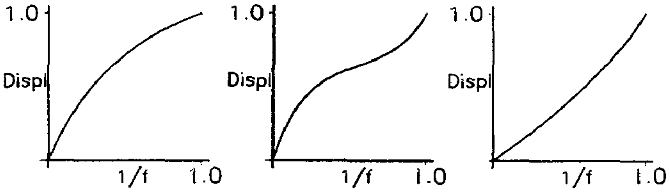


Figure 10
The confluence of two muscles

The modelling of the visco-elastic nature of skin as discussed has many variables and the cosine model is one possible solution to establishing a non-linear interpolant. Provided that the point of attachment is static and the muscle insertion into the skin has maximum displacement, any 'ramp' can be described to control the interpolant. The following examples Fig 11, where Fig 12 relates to (a), Fig 13 relates to (b), Fig 14 relates to (c). Illustrate the displacement activity where f is a function of (K.A.R.x). This allows a more flexible approach to the modelling of the elastic nature of skin.



(a) (b) (c)

Figure 11

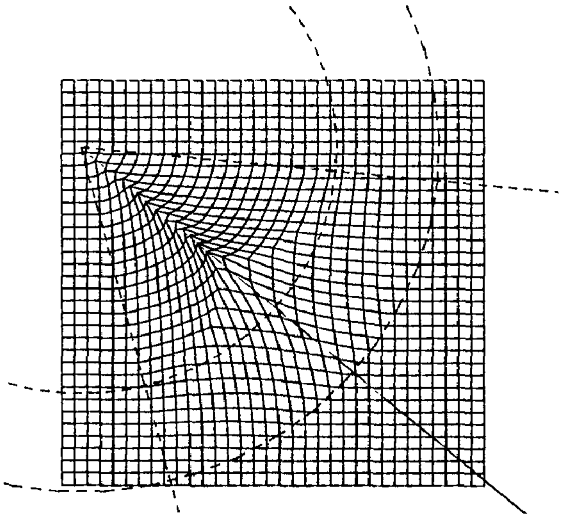


Figure 12
A three-dimensional muscle vector laying in the x y plane. Zone of influence 35.0, fallstart 7.0, fallfin 14.0, muscle spring constant 0.3 relating to (a)

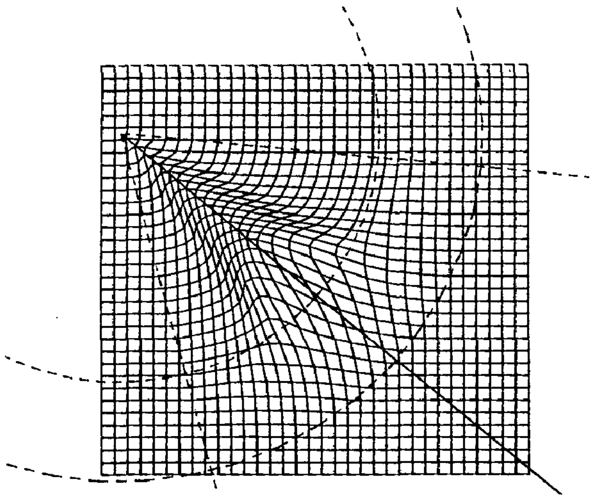


Figure 13
Same parameters as in figure 12 relating to (b)

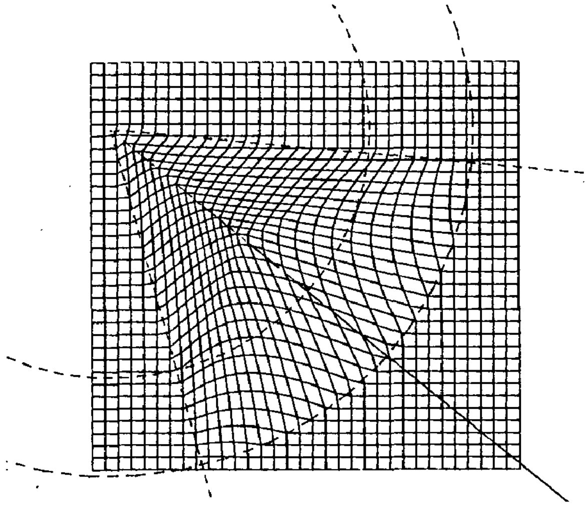


Figure 14
Same parameters as in figure 12 relating to (c)

7. The image synthesis and model operation

Polygonal data structures have been shown to be an acceptable mode of modelling facial topologies [5][7], and were adopted in this research for ease of use. The nature of the muscle model described above allows a free range in polygonal construction. This has proved to be important in the modelling of real people's faces that require specific topologies for recognition purposes Fig 15. However it remains important to maintain a mesh that is as regular as possible, to avoid polygonal intersections and 'facet popping' when the model is articulated. This can be remedied by increasing the density of polygonal detail where the curvature is higher. Additionally, all the facets need to be triangulated to maintain planer polygons for the renderer.

The heads shown Fig 15- 22 were modelled using photographic techniques [6] and mirrored about the meridian of the face. Although neither real faces nor the motional dynamics are symmetrical these are not problems as the muscles can operate independently on both sides of the face. For the simplicity of use, the faces illustrated were assumed to be symetrical in order to reduce the time-consuming effort of data duplication.

The eyelids were constructed from the existing vertices of the face to create five curves, three for the upper lid and two for the lower. The upper lids rotate about a horizontal axis to close the eyelids. Swept revolutions of profiles created the eyeballs that have controls for the dilation of the pupil and the focusing of the eyes. Highlights were important in giving a realistic effect and this was achieved either by using the Phong renderer or by extracting facets and shading them white. The teeth were simply formed from sets of Bezier curves that were set back into the mouth cavity. The lower teeth are rotated with the jaw. The positioning of the muscles was achieved by identifying key nodes on the face [18] and relating them to the computer model in three-dimensional space for the location of the muscle vector head and tail.

The model is implemented as a program that is parameter driven. The parameters are created in data files that control all the muscles, jaw rotations, eye focusing and the eyelids. The program generates polygonal or vector descriptions that can be rendered as desired. Ten muscles were implanted into the facial topology, representing those that are the required action units (AU) for FACS. Each linear muscle has parameters for:

• Zone of influence	half angle in degrees	Ω
• Fallstart	real radial distance	Fs
• Fallfin	real radial distance	Ff
• Muscle spring constant	$0<K<1$	
• Elasticity	$E >= 1$	

For the sphincter muscle:

• Tension	$0<T<1$
• Lx Ly	longitude and latitude real distances

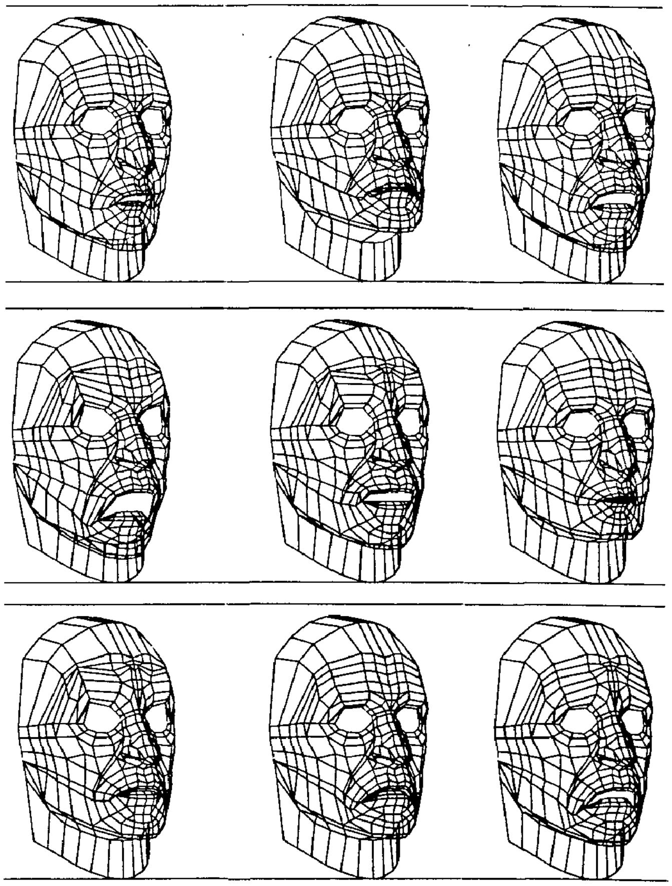


Figure 15

Illustrated are nine different facial expressions in both the upper and lower face on an alternative facial topology. Seven muscles (linear/parallel and sphincter muscles) were utilized with the jaw rotation to represent some of the actions from the Facial Action Coding System

8. Future Developments

- To increase the realism of the muscle model, the addition of creasing and buckling of the flesh as the muscle contracts would be advantageous. Most buckling occurs at right angles to the direction of contraction. By calculating the contraction length of the muscle vector and comparing it to the elasticity of the flesh convincing results could be produced.

- The flow of skin over the bone identified by Badler [1] could be solved by creating muscle vectors that curve round the underlying structure, in much the same way as real muscle, This however relies on the creation of an accurate model of the cranium and mandible.

- A more fundamental approach to the construction of the face needs to be taken that could encapsulate the widest range of facial types. Utilizing indices that are relevant to cranial form [18], the underlying structure of faces could be created according to sex, age and race groupings. More importantly, this underlying structure would indicate the precise position of the facial muscles. Additionally the mandible while being the only jointed bone, is not articulated by the muscle model. By ascribing those muscles responsible for the motion of the jaw more complex articulations could be achieved, of the lateral movement of the jaw during mastication.

- For speech, many of the problems associated with lip synchronization occur because of the co-articulation of phonemes. A simple parser that looked at the current, previous and next phonemes could establish what mouth shapes need to be created.

- The Phong renderer displays 'plastic' faces in a uniform manner, and texture-mapping real faces onto the polygon mesh would greatly enhance the realism, for example local texturing, such as stubble round the chin. Likewise hair could be grown in a particle fashion or texture-mapped.

- Finally, as the number of controlling parameters increases, it is evident that motional characteristics of the six primary emotions [9] could be grouped together to perform specified tasks. The development of a task-level system [21] would allow the global control over the complex motions of the face, while maintaining explicit controls over the facial details.

9. Conclusions

What has been presented here is a model for the muscles of the face that can be extended to any non rigid object and is not dependent on specific topology or network. A combination of parameterized techniques with the muscle model has been designed to perform complex articulations in reference to a notational-based system.

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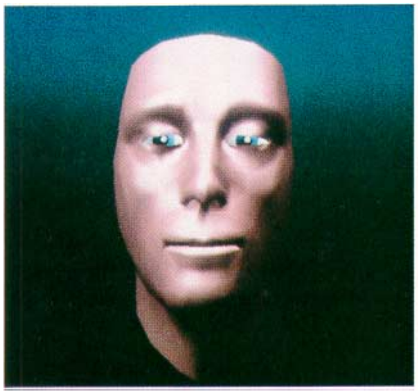

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Figure 16
Neutral face with the muscles relaxed

Figure 17
Happiness the corners of the lips are drawn back and raised obliquely by the zygomatic major muscle.

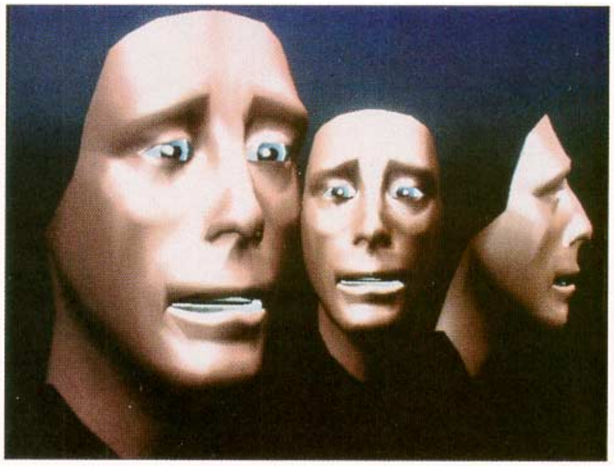

Figure 19
Fear the inner brows are raised by the inner frontalis muscle, the eyes are wide with pupils dilated. The jaw is rotated and the lips drawn back.

Figure 21
Anger the brows are lowered and the inner part drawn together. The jaw is not rotated and the lips are tight.

Figure 20
Disgust the alaeque nasi muscle raises the upper lip pulling the skin around the nose and causing the nostrils to dilate.

Figure 22
Surprise the brows are curved and high, the eyelids wide and the pupils dilated.