The Making of a Film with Synthetic Actors

N. Magnenat-Thalmann

Rendez-vous à Montréal [1] is an animated film that uses advanced computer techniques to achieve such effects as reincarnating the film stars Humphrey Bogart and Marilyn Monroe. It was directed by N. Magnenat-Thalmann and D. Thalmann and produced with a team of 10 people. The main purpose of *Rendez-vous à Montréal* is to show that true synthetic actors can be created. The film represents a technological breakthrough that opens new vistas in motion pictures, television and advertising. With this technique it will be possible to produce short films or motion pictures featuring any celebrity in any situation.

The film premiered in May 1987 at the Canadian Engineering Centennial Convention, which was attended by about 3000 delegates; excerpts were shown on six television channels the same week. Outside Canada, the first show was at CG International '87 at Karuizawa, Japan, and large excerpts were shown on the NHK channel 9 news program. Since that time the film has been shown at several festivals, including the Banff Festival, the Hiroshima Festival, the Montreal World Film Festival, the Women Film Festival in Hollywood, the Rio de Janeiro Festival, the Abitibi-Temiscamingue Festival, the Monte-Carlo Festival and the Stuttgart Festival. It was shown throughout the summer of 1987 at Montreal's EXPOTECH, the largest scientific exhibition ever held in Canada. An exhibition about the making of the film was shown in Canada and Europe.

Scenario

The movie begins in the hereafter, where Humphrey is bored and longs to live again. He thinks of Marilyn; he calls her many times and begs her to return to earth with him. The head of Marilyn grown old appears; she accepts. Humphrey then sets up a rendezvous with her for the next day at 10:00 PM at the Bon-Secours market in Montreal. Both actors disappear in the night while making faces at each other.

They come down from a starry sky into the Bon-Secours market; we hear footsteps and the sounds of the city in the background. We do not see Humphrey but we hear him think out loud. He hesitates, he looks about for the entrance, he finds it and enters the building. We come to a room where we see a clock that strikes 10 times, reminding us that time is a factor again.

Marilyn appears motionless and made of marble. She has not returned to life yet. In reply to Humphrey's questions, she turns into gold. Humphrey fancies her and sends her a kiss that awakens her. She appears in all her splendor. They take each other's hand and the romance begins.

Creation of the Actors

Planning

Since modifications of an existing synthetic object are very expensive in terms of design time, it is important to plan the construction of a synthetic actor carefully. Consideration should be given to how the object will be divided into parts. Should the hand, for example, be constructed in one piece, or should the fingers be separated? If a part has a symmetrical axis, it is more economical to construct only

ABSTRACT

The author explains how to create a film involving synthetic actors and describes in particular the making of the film *Rendez-vous à Montréal.* The scenario of the film and the construction of actors are presented. The animation of actors is separated into three parts: body animation, hand animation and facial animation. The choreography of the complete film is then explained: decors, cameras, lights and actors.

Fig. 1. N. Magnenat-Thalmann and D. Thalmann, *Rendez-vous à Montréal.* Plaster model of Marilyn's head.

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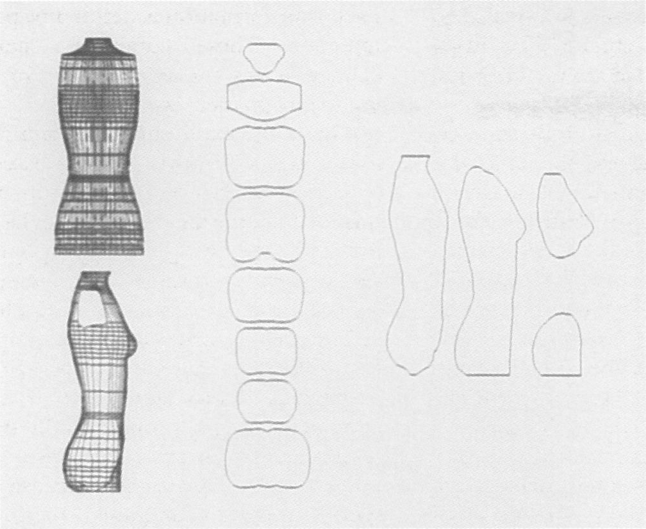


Fig. 2. N. Magnenat-Thalmann and D. Thalmann, *Eglantine*. Slices and reconstructed torso in wire-frame.

Fig. 3. N. Magnenat-Thalmann and D. Thalmann, *Eglantine*. Completely reconstructed actor in shading.

half of the part and then use a symmetry operation to get the whole. Although faces are not perfectly symmetric, they are generally considered as symmetric. Such are the choices of the designer and the animator. Their decisions will depend on the details required for each object, which in turn are strongly related to camera motion. When all the parts of a synthetic object have been created, they should be composed to generate the complete object. Although the separation into parts should be planned at the beginning, the composition process is only performed at the end, when all the parts are completely constructed. Once a satisfactory model is complete, we apply the digitizing technique. The model or object to be digitized should be large enough to allow the drawing of facets and vertices on it but small enough to be easily photographed. Any material may be chosen for the object; however, the surface should be of a light color and non-reflective to allow the drawing of lines and photographs.

To indicate to the computer the character's figure, we need to have either the actual person or a plaster model (life-size or reduced). In the case of actors who are dead, we rely on both photographs of the actor at a certain age and a live model who has about the same dimensions. The methodology differs according to the part of the person to be reproduced. For the head, teeth, hands, arms and fingers, a sculptor creates plaster models from the photographs of the real person (Fig. 1). As an aid, the computer has in its memory the three-dimensional shape of the character. The sculptor then can ask the computer to display the character according to several viewpoints. The cast of the body is made from the live model.

Digitizing

The most direct 3D digitizing technique is simply to enter the 3D coordinates using a 3D digitizer. Three types of such devices are now available: devices based on three orthogonal magnetic fields, devices based on three sound captors, and devices based on laser light [2].

A classical way of creating 3D objects is by 3D reconstruction from 2D information:

1. Significant points or grids are drawn onto the object.
2. Four orthogonal pictures are taken of the object.
3. An appropriate coordinate system is drawn for each picture.
4. Each point is identified by a number. Points have to be identified in at least two pictures to compute the X-, Y- and Z-coordinates of each point.
5. After placing the pictures on the digitizer, the user marks points that determine the boundaries of the pictures and those that identify the coordinate systems.
6. For each point, two different positions are successively marked.
7. Connections between the points are identified by numbers: this defines the strokes of points in wire-frame models and grids in facet-based models.

Another popular method consists of reconstructing an object from a set of serial cross sections, like tracing the contours from a topographic map. Several reconstruction methods are possible. This technique was used in the film *Eglantine*, directed by N. Magnenat-Thalmann and D. Thalmann. Figure 2 shows the slices and the reconstructed torso in wire-frame. Figure 3 displays the complete actress in a scene.

Facet modeling

The best-known technique of object representation describes an object by a collection of polygons [3]. Although often expensive in terms of CPU time, polygonal models of 3D objects are the most common. In these models, all objects are decomposed into polygonal faces. For objects such as cubes or regular polyhedra, this decomposition is very effective. But objects such as spheres or revolution surfaces require approximations. Unfortunately, large numbers of polygons often are needed to represent satisfactorily even comparatively simple shapes. In addition, the essential character of surfaces such as spheres is lost when they are approximated by collections of polygons.

To define an object using a polygon-based model, lists of vertices and polygons are specified where each polygon is defined by its vertices, identified by their rank in the list of vertices. A surface like the human face is irregular and composed of reliefs and depressions. It is important to choose vertices at the high points of reliefs and the bottoms of depressions. Dramatic angle variations between adjacent facets should be avoided, because they cause undesirable variations in shading, a physical phenomenon known as the Mach effect. The only solution consists of increasing the number of facets in regions where the curvature is significant. Because of the rendering process, the choice of facets to be drawn on the plaster model is very important. Facets should be planar, especially for shadow processing; for this reason, triangles are often chosen. However, it should be noted that quadrilateral facets require fewer vertices for the same number of facets. This may reduce the computer time considerably.

At this point, we turn our attention to the animation. First, the camera location must be considered: any curve (sequence of edges) that is shown from the side must have numerous vertices. As the camera eye nears the vertices, the number of vertices must be increased to make the surface smoother. The motion of the actor also enters into consideration. A curve (sequence of edges) may vary in animation. In this case the number of vertices should be increased for the maximum of curvature, to avoid any discontinuity of the surface during the motion.

ANIMATING THE HUMAN BODY

Skeleton

When the animator specifies the animation sequence, he/she defines the motion using a skeleton. A skeleton is a connected set of segments, corresponding to limbs, and joints, as shown in Fig. 4 [4]. A joint is the intersection of two segments, which means it is a skeleton point where the limb that is linked to the point may move. The angle between the two segments is called the joint angle. A joint may have at most three kinds of position angles: flexion, pivot and twist. *Flexion* is a rotation of the limb that is influenced by the joint and causes the motion of all limbs linked to this joint. Flexion is made relative to the joint point and a flexion axis that must be defined. *Pivot* makes the flexion axis rotate around the limb that is influenced by the joint. *Twist* causes a torsion of the limb that is influenced by the joint. The direction of the twisting axis is found similarly to the direction of the pivot.

In order to animate fully three-dimensional characters, the animator has also to position the skeleton according to the body of the synthetic actor to be animated. Apart from digitizing the shapes this procedure is probably the most time consuming. However, it is very important because all the mapping of the surface shapes is based on the skeleton position relative to the surface shapes. If a skeleton point is poorly positioned, the joint probably will cause abnormal surface deformations in the animation. This process is described in depth in another paper [5].

When the skeleton has been correctly positioned, the HUMAN FACTORY software will transform the character according to the angles required by the animation without any animator intervention. Figure 5 shows an example.

The mapping of surfaces onto the skeleton is based on the concept of Joint-dependent Local Deformation (JLD) operators [6], operators that control specific local deformation depending on the nature of the joints. They control the evolution of surfaces and may be considered as operators on these surfaces. Each JLD operator is confined to some uniquely defined part of the surface, which may be called the domain of the operator. The value of the operator itself is determined as a function of the angular values of the specific set of joints defining the operator.

Animation techniques

There are three main types of 3D computer animation [7]:

1. Image-based keyframe animation [8, 9]. Actors are characterized by their vertices; motion is specified by keyframes. Each keyframe consists of a series of values corresponding to the vertices for that keyframe. In-between values are calculated by applying an interpolation law for each corresponding vertex in the two keyframes.

2. Parametric keyframe animation [10, 11]. Actors are characterized by parameters such as joint angles; motion is specified by key values for each parameter. In-between values are calculated using an interpolation law.

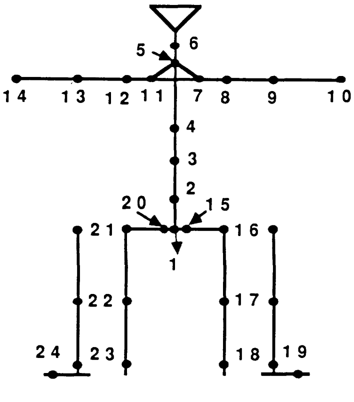
3. Algorithmic animation [12, 13, 14]. Actors are objects with a motion defined by a list of transformations. Each transformation is defined by parameters. These parameters may change during the animation according to any physical law.

The body, hand and facial animation described in this paper is based on parametric keyframe animation. In this method, the animator creates keyframes by specifying the appropriate set of parameter values; parameters are interpolated and images are finally individually constructed from the interpolated parameters. For each parameter, interpolation has to be computed using appropriate software programs. To animate (to move) a human body, it is necessary to use a specific program for human motion (in our case, HUMAN FACTORY). This program runs using a certain number of key values provided by the user. These key values are angles between the various body parts at certain times. For example, to animate an arm bending, it is necessary to give to the computer the angle of the elbow at different selected times. The software is then able to find any angle at any time. In-between values are calculated using bicubic splines. The animator may look at parameter values for any keyframe or interpolated frame. He/she may also obtain a wire-frame view for any frame.

Methodology of animation

The first step consists of determining the various key positions in terms of location in space and time; that is, for each key position, the position of a fixed point and the values of the vertebra joint angles are found. It is essential to be sure that the vertebra joint angles are perfect for the entire sequence before determining the other angles, because any modification of

Fig. 4. A basic skeleton. The legs are represented twice, in order to show feet with a correct orientation.



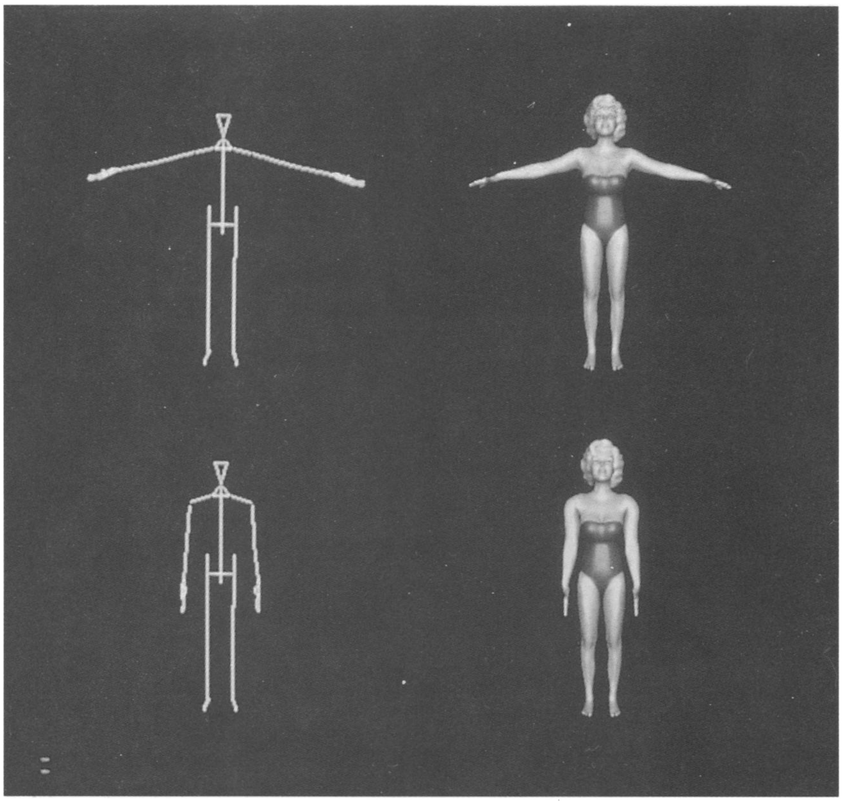
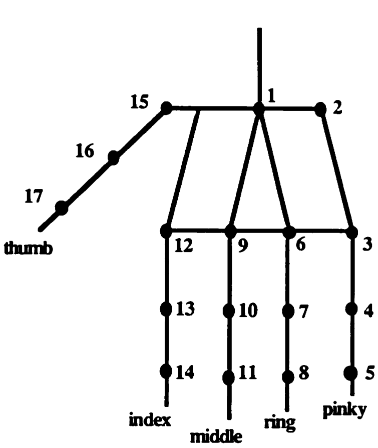


Fig. 5. Body mapping: basic skeleton (top left), basic actor (top right), skeleton with bent arms (bottom left), actor with bent arms (bottom right).

the vertebra joint angles generally implies a modification of the angles of other joints. Once the vertebra motion is defined, other angles are defined in a logical way moving from the center to the extremities (for example, vertebrae, shoulder, clavicle, elbow, wrist, fingers).

The problem of interpolation may be summarized as follows: given a certain number of points, find a curve passing through these points. The simplest method consists of joining the points by straight lines. However, if this method is used for animation, it causes a lack of smoothness that considerably alters the motion. A better interpolation is based on piecewise continuous interpolation of the curve by cubic functions. The interpolating curve must be continuous at the given points only up to a certain order. The Kochanek-Bartels method of spline interpolation allows control of the curve at each given point by three parameters: tension, continuity and bias [15]. A time value should be added to each control point to control the motion. The method is valid for interpolation between scalar values such as angles and vector values such as positions. We shall use this technique for calculating the interpolation of angles in the animation of human bodies, the interpolation of facial parameters and the interpolation of control points for the design of camera and light paths.

Fig. 6. Skeleton of a left hand.



ANIMATING THE HANDS

Technique of hand animation

Hand animation is also produced using angle key-values. The transformations are more complex, however, because fingers inflate when they bend and the palm deforms (tenses, contracts). For the animator, the hand is simply composed of five fingers made of three jointed line segments, linked to the palm; 15 different angles control the finger movements. The animator selects key-values and the HUMAN FACTORY software automatically computes the in-betweens required to complete the motion. HUMAN FACTORY also determines finger inflation and palm shape based on angle values.

As shown in Fig. 6, the hand skeleton is a connected set of segments and joints. A joint is the intersection of two segments. The angle between the two segments is called the joint angle. There are three kinds of hand joints: the metacarpal joints (#1 and #2 joints), the joints between metacarpus and fingers (#3, #6, #9, #12 and #15 joints) and the finger joints (all other joints). Metacarpal bones are the small bones linking joints 2 to 3 and 1 to 6. The flexion of metacarpal bones may vary from 0 to 20 degrees. Metacarpal joints are important for the palm animation and other joints for the finger animation. All hand joints have a flexion angle, but joints between metacarpus and fingers also have a pivot angle. Figure 6 shows the left hand skeleton and Fig. 7 an example of hand animation.

Hand covering

Once the motion of the 3D character is designed, the hand needs to be covered with surfaces. As for the rest of the body, we try to separate completely the topology of the surfaces from the skeleton. This means that the hand may be constructed using any method: surfaces by sweeping, free-form surfaces or 3D reconstructed surfaces obtained from digitized projections. Our system transforms the surfaces into the wire-frame model, ensuring an automatic continuity between the different surfaces. This correspondence is based on a changing of coordinate bases that are independent of the segment length. This means that for the same set of surfaces, several bodies of different sizes may be obtained according to the segment length in the wire-frame models. In our approach, the animator has only to position his/her hand relative to the skeleton hand.

The mapping of surfaces onto the skeleton is also based on the concept of Joint-dependent Local Deformation operators. The case of the hand is especially complex, for deformations are very important when the fingers are bent, and the shape of the palm is very flexible. Figure 8 shows the hand mapping for the sequence of Fig. 7. Segments of fingers are independent and the JLD operators are calculated using a unique segment-dependent reference system. For the palm, JLD operators use reference systems of several segments to calculate surface mapping. In order to make the fingers realistic, two effects are simulated: rounding calculations at the joints and muscle inflation.

Object grasping

The animator may indicate to the HUMAN FACTORY software that an object has to be grasped. He/she provides the contact points between the hand and the object; then the software automatically determines the sequence of angles required to grasp the object.

To grasp an object, the hand has to be used, and the joints of the hand must move correctly. Two actions should be distinguished:

1. The various joint angles necessary to grasp the object must be determined. These angles should be defined to avoid any space between the hand and the object, and also to avoid any intersection between the hand and the object.

2. Once the object has been grasped, it has to be associated with the hand. For example, if the synthetic actor Marilyn grasps a book, it is obvious that the book has to move with her hand. When she turns her hand, the book must turn along with her hand. Yet it is the arm that essentially guides the hand to grasp the book and move it to a new position. So once the book is in Marilyn's hand, all her movements will make the book move too.

Positioning of the object may be controlled in two ways:

1. The animator manually selects the angles in order to grasp the object; the system indicates to the user when the fingers and the object have a common intersection.

2. The animator determines the vertex on the hand and the three vertices belonging to the facet of the object to be grasped. The flexion angles are automatically computed in order to make contact between a specific hand vertex and the object to be grasped. This calculation is performed using a binary search in order to make the distance between the contact point and the object less than some threshold value.

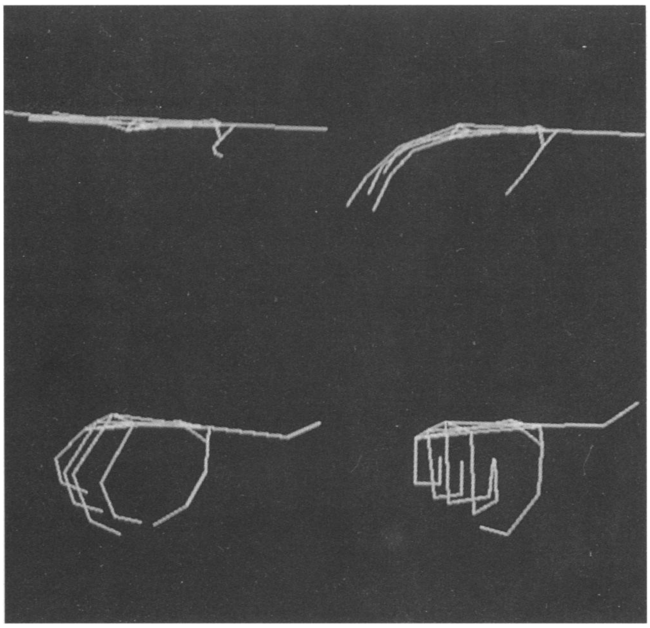


Fig. 7. Hand animation: skeleton.

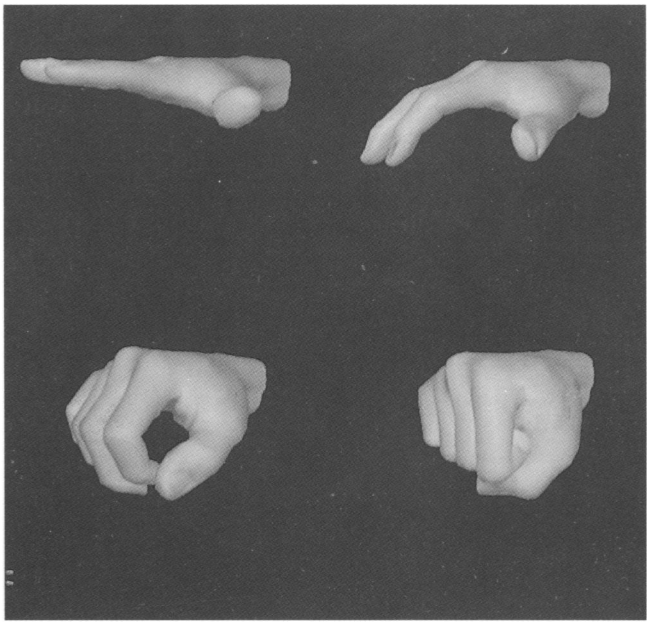


Fig. 8. Hand animation: mapped surface in Gouraud shading.

Generally, the animator starts his/her animation specification by positioning the hand at the best location relative to the object, without bending the fingers. This means that the chain 'shoulder-elbow-wrist' is defined with the maximum accuracy. Then one of the above methods is used.

Animating a Human Face

Principles of facial animation

Facial animation of synthetic actors corresponds to the task of an impersonator. Not only should the actors be realistic in static images, but their motion should be as natural as possible when a series of images is displayed in the form of a moving film. The face is a small part of a synthetic actor, but it plays an essential role in communication. Humans read faces for emotional and intentional meanings; some literally read lips. Imitating these often subtle signs is a particular challenge.

A synthetic actor must speak and display facial expressions at specified moments. This leads to the concept of a script for facial animation, that is, a sequence of facial expressions in time. For example, at time 0, the face is neutral, at time 3 the face is smiling and at time 5, it is angry. This means that to animate an actor's face, the animator must first build a certain number of facial expressions specific to the actor's character. The expressions are built by specifying those facial deformations caused by actual muscle movement: jaw opening, eye opening, face folds, etc. These deformations vary from one person to another. For instance, if we ask several people to open their mouths as wide as possible, we find the maximum aperture is not the same for everyone.

Phonemes

A facial expression for a synthetic actor is made up of a percentage of actions for each active facial parameter. There are two types of facial expressions: phonemes (speech) and emotions (joy, grief, etc.). A phoneme uses only the muscles of the mouth, to create those specific sounds we call speech. Each phoneme corresponds to a lip motion and a tongue position. For our film *Rendez-vous à Montréal,* we chose 28 basic phonemes from the symbols categorized by the International Phonetic Association. In our particular case, however, we ignored the tongue position to simplify the technical problems. For example, for the phoneme 'I' (as in 'KID'), the teeth are slightly open and the commissures are horizontally pulled toward the sides of the mouth (risorius muscle). To produce the sound 'I', we select 10% of the vertical jaw, 50% of the left risorius and 50% of the right risorius.

Once the animator has built the expressions, he/she animates the face by indicating to the computer specific expressions at selected times. For example, 'KID' will be pronounced by a character beginning with the phoneme 'K' followed by the phoneme 'I' a short time later and then the phoneme 'D'. The software then progressively will transform the facial expression corresponding to the phoneme 'K' to obtain the facial expression corresponding to the phoneme 'I' and then the one for the phoneme 'D'.

In addition to creating phoneme expressions, however, we also must imitate the natural human rhythm of speech. For this it is essential to study a real human voice, ideally the voice of the true actor (if there is one) corresponding to the synthetic actor. For example, we establish the vocal rhythm of the synthetic actor Marilyn by studying the actual voice of Marilyn Monroe. We use a magnetic tape player of the actor pronouncing a few words or syllables and measure the length of the tape corresponding to these sounds. From this length, we easily can compute the required time for each phoneme.

Fig. 9. Facial expressions.

Levels in facial animation

From the considerations above, we distinguish three levels of interaction for the animator: The first and lowest level is the level of control of facial parameters; the animator may decide how a basic deformation will appear on a specific synthetic actor. At the second level, the animator creates specific expressions based on the facial parameters. For example, he/she creates phonemes, a smile, a loving look. At the third level, the animator decides the timing of the animation by fixing certain expressions at various points.

As an example, at the first level, the animator may decide how the synthetic actor Marilyn will open her mouth, that is, its maximum horizontal and vertical openings, which are facial parameters. At the second level, the animator may decide to contribute these facial parameters to an expression like a smile. At the third level, the animator makes Marilyn smile at a certain moment. In other words, an animator may work only at the script level; however, in this case, he/she controls only the timing and the duration of expressions or series of expressions. He/she cannot create completely new expressions, except when they are combinations of existing expressions. The parameter level is not necessary when basic facial parameters for a synthetic actor already exist, as, for example, those for Marilyn Monroe and Humphrey Bogart created for *Rendez-vous à Montréal.* In this case, the animator can create any new scene involving the same actors. At the expression level, new expressions can be created using the facial parameters. Figure 9 shows examples of facial expressions.

REALISTIC ASPECTS

Colors

Once digitizing is finished and all facets are known from the computer, it is possible to color the actor or even to color each facet. The number of available colors is hardware-dependent; it may vary from two colors (black-and-white terminal) up to about 16.7 million colors. For realistic images, light plays an active role. When we consider, for example, a complex red object, we realize that many red tints are required to represent the object. In general, the production of realistic images using transparency, texture and shadows requires a very large number of colors.

But how do we select colors? If we limit ourselves to eight colors, we may use the standard color names; but for the thousands (or even millions) of colors need to produce a realistic image, numerical systems are essential. The most well known are the RGB and HLS systems.

Drawing style

Three types of drawings are possible on the screen:

1. The computer draws the edges of all facets—this is a wire-frame drawing.
2. The computer colors each facet according to the light source selected by the user.
3. The computer colors each object using a gradation based on light calculations. This is the most realistic representation. Unfortunately it is also the most complex and the most expensive in terms of computer time.

Reflectance and highlight for synthetic actors

Human skin is difficult to render because of its complex texture. However, its aspect may be considerably improved by using a suitable reflectance factor. Theoretically, there are two extremes of surface type: *ideal specular reflectors,* which are like perfect mirrors (e.g. polished brass, still water) and *ideal diffuse reflectors,* which correspond to dull matte surfaces (e.g. cork, chalk). In fact, most real surfaces are neither ideal specular reflectors nor ideal diffuse reflectors. For this reason, illumination models have been developed. These models break reflection into three components—ambient, diffuse and specular.

The *ambient* component of light does not come from any single source but is an overall illumination that comes from the surroundings (walls, other objects); it represents in fact a completely distributed light source. The *diffuse* component consists of light that emanates from a point light source but is scattered equally in all directions. Objects possessing only diffuse lighting attributes appear to be made of a dull, smooth plastic. The *specular* component simulates the reflection of light from a surface in some distribution about the angle of incidence. This represents the highlight, i.e. light concentrated around the impact point of the incident ray. The highlight has the color of the source light. There are typically two parameters to control the specular component: (1) the reflectance factor and (2) the highlight width w. The highlight width depends on the surface and determines how glossy this surface is; typically w varies from 1 to 200 and would be infinite for a perfect reflector. Large values of w correspond to metallic and shiny surfaces, while small values correspond to nonmetallic surfaces like paper.

A reflectance factor of 0.5 seems too plastic, because it is too reflective. For the synthetic actor Marilyn, the following values were used: skin, eyelash and eyebrow: 0.1; beauty spot and pupil: 0.01; nails: 0.9. The value of the highlight of the pupil has been set at 1; the default value of 5 is applied to the rest of the character.

Fig. 10. Facial expressions with zoom, illustrating variations of the camera view angle. Top left: view angle = 15°; top right: view angle = 30°; bottom left: view angle = 45°; bottom right: view angle = 60°.

SYNTHETIC CAMERAS AND LIGHTS

The role of synthetic cameras

One of the most impressive effects in computer-generated films is rotation around a three-dimensional object or entrance into a complex solid. Although these effects appear spectacular, they are in fact quite easy to produce. Typically, these effects are based on the motion of a synthetic camera. A synthetic camera is a software entity that uses a few input parameters to display, like a real camera, a 2D view of a 3D scene. This means that a synthetic camera performs all the geometric transformations needed to convert three-dimensional points into points in the two-dimensional image plane. A basic synthetic camera is characterized by at least two parameters: the eye point and the point of interest. The eye is a point that represents the location of the camera. The point of interest is the point toward which the camera is directed. A view angle also may be defined to control the width of the observer's view, as shown in Fig. 10.

A synthetic camera can simulate such typical effects used by camera operators as panning, tilting, tracking, zooming and spinning. Special effects such as the wipe effects produced by optical printers in conventional animation also can be produced using synthetic cameras.

Design of a camera path

One important task of the animator is to design the movement of the camera; the typical camera motion consists of guiding the eye and/or the interest point along a path. A path is in fact a curve containing time and space information. One of the best ways to create a path is with the use of splines. They are created as follows:

Step #1: Positioning of the first camera. The animator first decides the initial characteristics of his/her camera: eye, interest point and view angle.

Step #2: Creation of the first control point of the spline. Once the camera is well positioned, the animator defines the camera eye as the first control point of the spline.

Step #3: Creation of the other control points. A second point is then selected by moving the camera eye. The new camera eye is then inserted as the second control point for the spline. Other control points are created using the same procedure.

Step #4: Editing of control points. Each control point may be modified and new control points may be inserted between existing control points.

Step #5: Time control. A time can be defined either at each control point or at only the first and last control points.

Step #6: Spline visualization. All inbetween points should be displayed for control purposes.

Step #7: Definition of spline parameters. Default values for bias, tension and continuity should have been defined at each control point. Now the animator probably should change the spline by modifying these values.

Step #8: Creation of the spline.

A spline for the point of interest of the camera also may be created using a similar procedure. In this case, the point of interest of the camera is used to generate the control points instead of the eye.

The role of synthetic lights

Generally, four kinds of synthetic light sources can be defined to illuminate a three-dimensional scene:

1. ambient light, defined by its intensity, corresponds to light that is uniformly incident and is reflected equally in all directions by the surface.
2. directional light, defined by intensity and direction.
3. positional light, defined by intensity and location.
4. spotlight, defined by intensity, location, direction and concentration. Spots are light sources with a direction that may be controlled independently of the source location. A factor may determine the spatial concentration of the directed light source, allowing spotlights and floodlights to be simulated.

For any realistic computer-generated image, light sources have to be considered key elements in the scene. However, unless the light source is unique and located at an eyepoint or the illumination is very diffuse (as from an overcast sky), images are not complete without shadows. Unfortunately, algorithms for shadows require considerable computation time.

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