

A Facial Rigging Survey

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Abstract

Rigging is the process of setting up a group of controls to operate a 3D model, analogous to the strings of a puppet. It plays a fundamental role in the animation process as it eases the manipulation and editing of expressions, but rigging can be very laborious and cumbersome for an artist. This difficulty arises from the lack of a standard definition of what is a rig and the multitude approaches on how to setup a face. This survey presents a critical review on the fundamentals of rigging, with an outlook of the different techniques, their uses and problems. It describes the main problems that appear when preparing a character for animation. This paper also gives an overview of the role and relationship between the rigger and the animator. Continues with an exhaustive analysis of the published literature and previous work, centered on the facial rigging pipeline. Finally, the survey discusses future directions of facial rigging.

Categories and Subject Descriptors (according to ACM CCS): A.1 Introductory and Survey, I.3.7 Three-Dimensional Graphics and Realism

1. Introduction

Everyday, we see many faces and interact with them in a variety of ways: talking, listening, looking, making expressions. Creating convincing and appealing facial movements on 3D characters, like smiling or blinking, seems simple in concept. But, it requires deep understanding of the incredible complex system that lies beneath a face and very good knowledge of animation principles, to perfectly reproduce facial movements that look realistic. Today, facial animation is done through motion capture and/or manually by skilled artists, who carefully place and manipulate the animation controls to create the desired motion. This latter process is called *rigging*. We can think of *rigging a 3D character* as a process analogous to setting up the strings that control a puppet.

The entertainment industry is the main driver for the development of advanced computer facial animation systems. In films and videogames, the face and the facial expressions become fundamental to convey emotions to a character, requiring believable animations. But, generating realistic face movements is hard. Designing a unified, elegant, easy to use



Figure 1: Left: Kermit (*The Muppet Show*); Right: Chuck, from feature film *Planet 51* (Ilion Animation Studios, 2009). This figure illustrates how a puppet and a digital character can be expressive and empathic in very similar terms.

and flexible facial rig structure is often complex and time-consuming. Rigging a character usually starts at an early stage of a production. It is an iterative process that requires

an experienced artist (sometimes called character technical director or rigger) to understand what behaviors the character needs to perform. As facial models become more and more complex, it is increasingly difficult to define a consistent rig that can work well for every possible movement. It is common that after the rig is created an animator asks the rigger to create new controls, because the character needs to support new poses or simply needs to look better. Thus, the rigging process becomes a bottleneck in a CG production pipeline.

Current 3D animation applications such as Maya [Aut12c] include powerful tools for deforming and controlling models. These softwares can be used by artists to sculpt facial poses [Mar03] or to create facial skeleton structures to rig a character [War04]. In addition, there are a set of plugins exclusively designed for facial rigging like Bony Face [SF12]. They hide the complexity of the underline rig structure and the deformation algorithms, like soft tissue solvers, providing animators with a high-level facial user interface.

The most important feature of each face and also the main difficulty during animation, is its uniqueness. This survey describes the challenges that arise when preparing a character's face for CG animation and the different approaches adopted during the past four decades. *Facial Animation* is based on ideas pioneered by Parke [Par72], who introduced the first parameterized facial model allowing direct creation of facial deformation by defining *ad hoc* restrictions or by deriving guidelines from the structure and anatomy of the face. Parke anticipated many challenges that rigging techniques would encounter in the future, including how to determine expression parameters to control facial poses and how to define the appearance of the face model geometry. In consequence, modern rigging techniques have increased their popularity in a wide range of animation tasks, some of which are discussed in Section 3.

The main challenge in rigging a character is to accurately *mimic* the deformation of an anthropomorphic face. This survey gradually introduces the rigging concepts for facial animation and its current state for off-line and real-time systems. Due to inexistent categorization, we divide the requirements in two groups: morphology and behavior. In addition, the lack of a formal rig definition lead us to re-think its essentials and propose a *rig data-flow structure*, which describes how to process the motion data, interpret the input, define the user interface and the inner structure and deform the resulting geometry (Section 4.1). The final goal is for the reader to completely understand the field of facial rigging.

This survey is organized as follows. It starts by discussing the analogy between a marionette and an animation rig (Section 2). Next, describes the two main application domains, off-line systems and real-time interactive systems, as well as an overview of the rigging process (Section 3). Section 4 presents a historical overview of the origin of the rigging approaches, introduces the fundamental concepts and discuss

the main challenges. The core of the survey is described in detail in Sections 5 and 6. Section 5 talks about the facial morphology and the importance of facial features when designing a rig, while Section 6 discusses the different approaches to create a rig and how to generate facial behaviors through it. We conclude with a discussion of future trends and open problems (Section 7)

2. A Rig Analogy

It may not come as a surprise that the best analogy for an animation rig is the control setup of a marionette. If one looks at a model as a digital version of the body of a marionette, the control rig allows to pull the virtual strings attached to a model, conferring animation. In fact, since the early 1960s, with the pioneer work of Lee Harrison III [Stu98], computer graphics researchers try to mimic real marionettes with digital puppeteering.

A marionette is an articulated doll, having each joint connected to a control frame by a string. The manipulation of this control frame causes the strings to stretch or shorten, producing movement. The number and position of joints dictates the amplitude and smoothness of the movements, but also increases the complexity of the manipulation.

A virtual character is a computer representation of a model, where rig control points can be attached to selected areas. These rig control points affect the areas they are attached to in accordance with any geometric operation (translation, rotation and scaling) applied to them. They are not, usually, directly manipulated, but by the means of a digital interface. The number of controls defines the subtlety of the achievable expressions. A higher number of control points in the rig means smoother animations, but also a more complex system to animate and maintain.

This almost one-to-one correspondence between the physical process of puppeteering and the virtual rigging and animation processes has served as a inspirational guiding line for researchers and artists since the inception of the field, for bringing, virtually, the ilusion of life (See Figure 1).

3. Application Domain

The face is capable of reproducing consciously or unconsciously multitude of subtle expressive variations, generating a wide range of expressions [Bad95]. Those subtle movements allow human beings to duly communicate their emotions and intentions [TKC01]. The same idea applies to the face of a virtual character, in which facial features and performance are key to the character's believability [UG05]. Thus, facial expressions become the key component for non-verbal communication and an important element for transmitting emotions in virtual characters. Stoiber et al. [SSB09] consider facial performance essential to reproduce synthetic models that resemble a specific person. However,

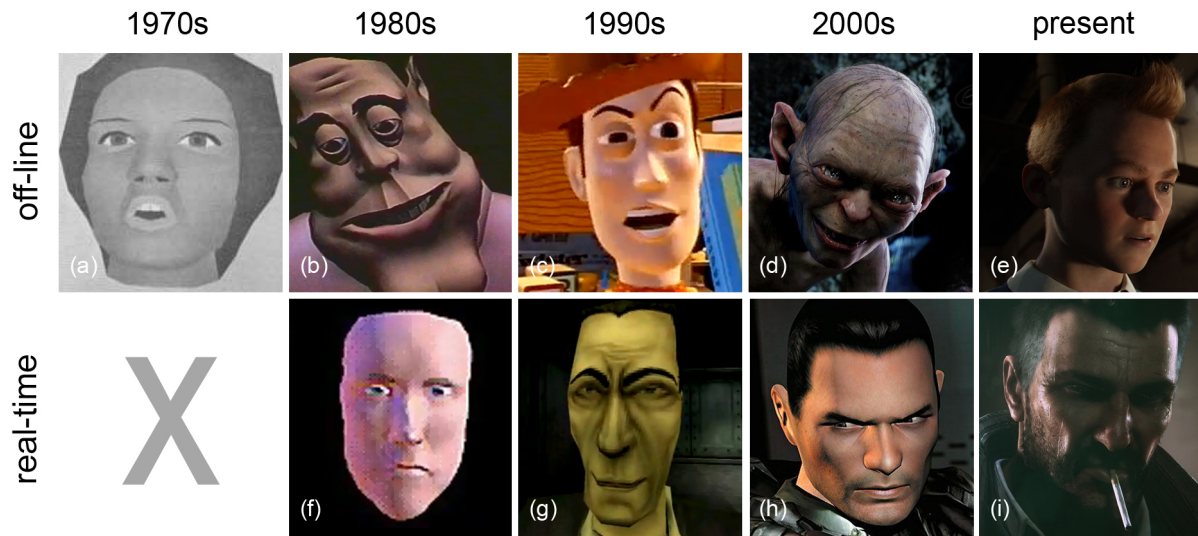


Figure 2: Evolution of character facial rigs and animations since the 1970's until today. *Off-line:* (a) Parke's [Par72] facial parametric model, (b) Tony de Peltrie [BL85], the first short animated film to use a parameterized facial model, (c) Toy Story [Por97], the first CGI film introducing the twelve principles of animation, (d) Gollum [Rai04], realistic CGI character in a leading role in a live action film, (e) The Adventures of Tintin (2011), the current state of the art with performance capture in an animation film; *Real-time:* (f) Mike the Talking Head [Deg88], first real-time virtual puppetry, (g) Half-Life (1998), early facial animation on 3D video-games, (h) Doom 3 (2004), bone-based facial rig for video-games, (i) The Samaritan Demo [OPW* 11], the current state of the art in facial animation in real-time.

humans are capable of identifying unnatural behavior, due to their everyday familiarity and sensitivity to facial appearance. For this reason, most authors agree that facial animation is so hard to achieve and also a powerful story-telling instrument in the Entertainment Industry, as illustrated by [Hau11].

Within the entertainment industry, the applications can be divided into *off-line systems* and *real-time interactive systems*. Off-line systems, mainly used for feature films, visual effects or TV broadcasting, require high realism and accuracy to reinforce the spectators suspension of disbelief. While real-time interactive systems, like videogames, virtual reality and digital puppetry, require a trade off between believability and fast computation.

Facial animation techniques were first introduced in *off-line systems* by Parke [Par72] in the film *Futureworld* (Richard T. Heffron, 1976). However, the first CG animated human character to display emotions through his face is *Tony de Peltri* [BL85]. Since then, the realism expectations quality of the audience drive the development of technology for films. Facial expressions enhance the immersive experience of the spectator, so any inconsistency in appearance or non-realistic expression can ruin the atmosphere. *The Adventures of Tintin* (S. Spielberg, 2011) is an example of a full CG animation film, while *Rise of the Planet of the Apes* (R. Wyatt, 2011) is an example of a real live film with CG creatures.

Figure 2 shows an overview of the evolution of facial animation since the 1970s until today. These results were only possible, because in film productions there are no rigging computation constraints when rendering the models.

In *real-time interactive systems* facial animation plays an ever increasing role. Facial rigging arises as a necessity to include interaction in the applications. The first system to adopt it was *Mike the Talking Head* [Deg88] a digital puppet demo shown at SIGGRAPH 88 Electronic Theater. Early videogames could only generate facial animation with full motion video (*Dragon's Lair*, Advanced Microcomputer Systems 1983), 2D Sprites (*The Secret of Monkey Island*, LucasArts 1990) and 2.5D techniques (*Wolfenstein 3D*, Id Software 1992). In the late 90s, with the *rise of the 3D age* in videogames (Quake, Id Software 1996), animation improved by employing full 3D body animation mainly used for action games, because the technology still does not support facial animation for story-telling. One of the first examples of facial rigging in videogames was *Half-Life* (Valve, 1998), which used the Quake Engine (Id Tech 1), bringing videogames to the next level of interactivity as it included basic facial expressions and speech. Today, the new GPU architecture present new algorithms for blend-shape and tessellation [BB04, Bun05] allowing the creation of wrinkles and morphing to produce real-time facial synthesis with photorealistic quality (*UDK Samaritan Demo*, [OPW* 11]).

3.1. The Rigging Process

In the late 80s, Lasseter introduced the concepts of classic animation into CG productions [Las87]. Meanwhile, Degraf in *Mike the Talking Head* [Deg88] experimented with performance animation, where for the first time an animated character was able to interact in real-time with a person, controlled by an operator. These two events trigger the necessity to divide the animation process in two roles: the animator or performer and the technician. But, the rigger role has not yet been defined. It was only in the middle of the 90's that the rigging concept emerged due to the increasing need to have characters perform complex actions. As far as we are aware, Kinemation (The Advanced Visualizer, Wavefront Technologies) and Power Animator (Alias Research) show the initial steps towards the creation of tools that lead in 1998 to the consolidation of the rigging process with Alias/Wavefront's Maya. It presents the concepts of *character setup* also known as *character rigging* or simply *rigging*, as referred later by Maestri [Mae01] and Schleifer et al. [SSMCP02].

“Rigging is the process of taking a static, inanimate computer model and transforming it into a character that an animator can edit frame-by-frame to create motion” [FMV*04]. From a technological point of view, McLaughlin and Sumida state that character rigging is the system engineering process that allows surface deformation [MS07]. Thus, we can understand rigging as the technique for creating a rig that enables an artist to manipulate a 3D model to create motion on a 3D character. Therefore, rigging links the modeling and animation process within a traditional animation pipeline.

4. The Facial Rig

To fully understand the definition of a rig, it is necessary to go back and analyze its origin and its importance in animation. A simple 3D object like a cube might be simple to animate using basic transformations (e.g. rotation in space). But as soon as we start working with complex deformable models, like faces, controlling and editing the model stops being trivial. If we leave aside the artistic aspects of animation, the main problem relies on setting efficient specifications and motion controls to generate realistic movements. Animating one object defined by a single reference point is straightforward, however animating complex models that have many regions moving, with different behaviors and conditions, is extremely difficult. The oldest method to animate 3D models is to use a keyframe system to interpolate all the vertex positions in a given period of time. But manipulating each vertex to get the desired shape quickly becomes impractical when the complexity of the model increases. This technique requires a lot of input from the artists, turning the animation process laborious and time-consuming.

Luxo, Jr. (Pixar, 1986) shows a shift on how animation was conceived, by introducing control techniques into the

process. The motion in *Luxo, Jr.*, a desk lamp, was achieved by keyframe animation, where each key was a state of the lamp *articulated structure* and the overall motion was defined by a spline curve. This is not a full control system but it allows a high degree of manipulation, instead of having to edit each vertex of the model [Las87]. Witkin and Kass (1988) introduced the concept of space-time constraints as a method that allows physically based animations through the configuration of parameters in a high-level control interface. Thus, the animator was able to specify (i) what the character has to do, (ii) how the motion should be performed, (iii) what the character's physical structure is and (iv) what physical resources are available to the character to accomplish the desired motion [WK88].

But, what is an articulated structure? This term came out of robotics; in CG animation it can be defined as a skeleton, a group of joints connected to each other that enables the different regions of the structure to move. It is an abstraction layer that is never rendered, located inside the model and binded to the surface, which only exists to ease the control of the object [Wat00]. Sometimes, additional intermediate layers are created between the skeleton and the surface to simulate, for instance, muscle behaviors [Wat87]. Last, to add motion to the control structure the animator can use forward kinematics or inverse kinematics techniques [VB08].

The advances in animation control methods that emerged from robotics and stop-motion gave origin to what we know today as *rig* [KHSW95]. However, the following 10 years show little development on new rigging techniques. It was only in the mid 90s that we began to see evidence of new approaches that introduce two main layers when creating a rig: the *transformation* and the *deformation*. A transformation is defined as the manipulation of an object and the deformation as the change of shape of the components of the object. Therefore, the rig concept is an evolution of control methods that range from simple 3D objects up to complex 3D objects, like a face. The ultimate goal is to allow artists to control the transformation and deformation layers intuitively. In the end, finding the optimal solution to create a facial rig requires a complete understanding of how the transformation and the deformations of the rig structure affects the 3D model.

4.1. Rig Fundamental

The structure that controls the model, the *rig*, determines the quality and the number of the potential animations. We can find in the bibliography many consensual definitions of what is a rig [Muc04, CBC*05, Sch06, GZH*10]. In a broader manner, a character rig is a set of controls that allows an artist to manipulate a character similar to handling the strings of a virtual puppet. Hence a rig should be looked at as a layered system of deformer, expressions and controls [Kel10]. From a more technical point of view, a number of authors agree that defining a character rig involves creating an articulated musculo-skeletal system that receives in-

put animation data in order to deform the character's model [CBC*05, BP07, JMD*07, MS07, O'N08, MAF10, Bay11].

We can infer that a rig is defined as a structure that performs a specific action. In a 3D model the structure becomes an internal configuration that determines how an input motion will deform the geometry. If the geometry is a 3D face model the input motion data must imitate the anthropomorphic movement in the model. The *rig data-flow structure* is described in Figure 3. The first stage is to determine the requirements in terms of shape, defining the morphology of the character, and movement, defining the behavior of the character; followed by the acquisition of the input motion data that triggers the elements of the rig structure. The final stage consists on deforming the geometry.

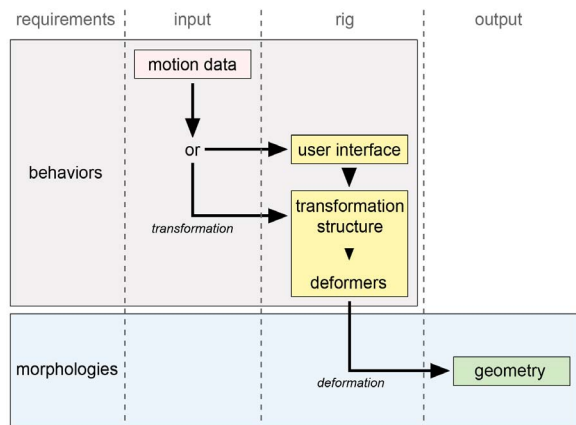


Figure 3: Overview of the rig data-flow structure. Stages: (i) Set the requirements by defining the morphology (shape) and behavior (movement) of the character; (ii) input motion data acquisition that activates the rig structure; (iii) geometry deformation.

A common concern in rigging is how to transform the input motion data into geometry deformation attributes. Then, the rig structure is divided into three layers, which are not mandatory, in order to perform the data conversion: (i) the *user interface* allows the artist to control the input data, (ii) the *transformation structure* defines the origin and position of the model, and (iii) the *deformers* modify the geometry of the model based on the transformation (see Figure 3 rig module).

The rig data-flow structure concept can be used in a production environment as part of the *content creation pipeline*, which is divided into the following stages: modeling, rigging, animation and rendering [Ker09]. Raffaele Scaduto emphasize that “In any basic *character driven* production pipeline character setup holds a very critical place. After the initial pre-production design work is done, in production the characters need to be modeled, rigged and animated.” [SSMCP02]. Notice that in the rig data-flow structure, presented in Figure 3, the requirements are defined in terms of

shape or visual style and movement during pre-production. Next, during the production stage the geometry of the model is created based on the visual requirements. After the geometry has its final look and the deformable models are determined, it is possible to define the rig and have a model ready to animate. (See Figure 4).

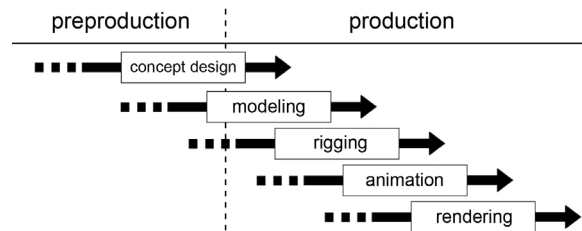


Figure 4: Different stages in a production pipeline.

4.1.1. The Rigger

The person responsible for rigging a character is most commonly known as Character Technical Director, Rigger or Technical Animator. Its main responsibility consists in defining the control parameters and interface that an animator will use. This means (i) making sure that a character's 3D model is functional, aesthetic and has a complete range of motion; (ii) maintaining ongoing support for all of the characters' controls; (iii) negotiating compromises with the animation department to try to minimize problems and inefficiencies, thus balancing the visual needs with the technical expense of rigging difficult elements [FMV*04, Mar08]. From a production point of view, it is crucial to ensure the communication and fluid relationship between the modeling and animation department. The modelers define the guidelines of the character (e.g. wireframe, size and proportions), while the animators define the movements and are in fact the end users of the rig system. As Les Pardew states: animators are observers of *life and motion* [Par08]. They care about achieving good visual results, transmitting clear expressions of the character's emotions and accurately applying the principles of animation [TJ81, Bla96, Wil01, LR12, Mon12]. Taking into consideration the previous description the rigger needs to (i) know what parameters and user interface (UI) to provide and (ii) what techniques should be used to implement the system. Finally, the rigger is responsible for establishing the appropriate surface controls and providing the animator with an effective, efficient, and intuitive interface [PW08].

4.1.2. Rigging Production Pipeline

In Section 3 we mentioned that within the entertainment industry the applications can be divided into off-line systems and real-time interactive systems. This distinction leads to the creation of different rigging production pipelines that depend on the type of application (e.g. films, videogames and puppetry). The difference relies on that the off-line systems

only one rig is required for animation purposes (see Figure 5), while in real-time systems it is necessary to define two rig modules, one for animation and the other for rendering (see Figure 6 and 7). In off-line systems it is first necessary to create the animation rig and bake all deformations that came out from the animation data, which will then generate the render file [SSMCP02]. In real-time systems the deformation of the geometry and the rendering needs to be calculated in run-time. Figure 6 describes the data flow for real-time applications, like videogames, where the animations are stored and then triggered by a specific action [LO12]. Furthermore, Figure 7 shows the data flow for real-time interactive applications, like virtual puppeteering, where the animation is rendered based directly from the users input motion, no data store is required [DS10]. Also notice that the content creation pipeline is simplified. Although described that the rig fundamentals, in terms of content creation, are the same. The main differences between both systems are the memory and process power. In real-time platform this is a tremendous constraint, while in off-line systems the impact is not critical.

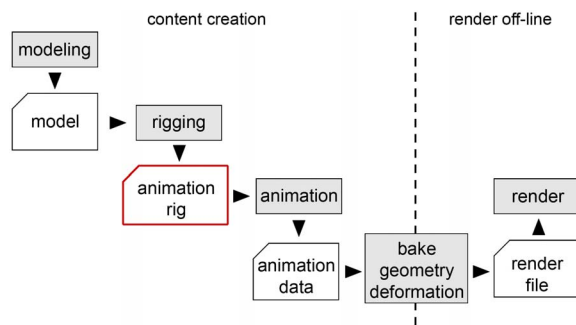


Figure 5: Off-line Systems (films): off-line rigging process.

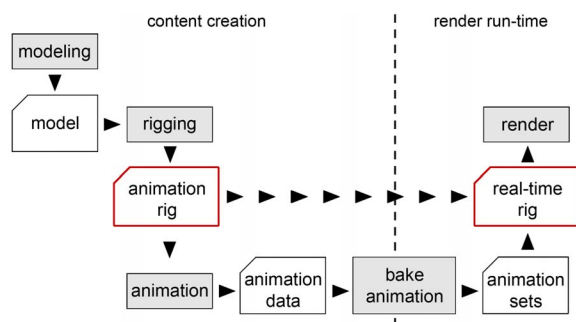


Figure 6: Real-time Systems: real-time rigging process with triggered pre-generated animations.

4.2. Facial Rigging Challenges

Despite of the type of rig created for off-line or real-time systems, the conditions that constraint the creation of the

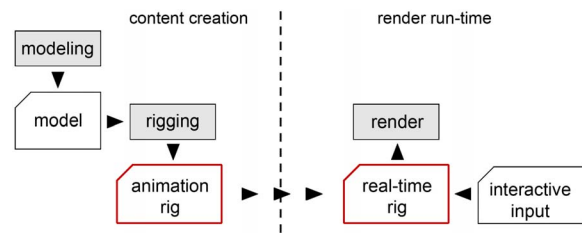


Figure 7: Real-time Systems (puppetry): real-time direct manipulation rigging process.

control structure are the same: the morphology and behavior definition of the face model, the lack of a rig standard and the complexity of the interaction model.

Diversity of faces: in realistic CGI illustrating a human face can be very complex, due to its different features. These features emphasize their uniqueness, caused by the variations of size and proportions of bones and muscles [EF75]. In addition, artists extended the scope of characters by including cartoons and fantastic creatures that not always follow the human structure [RCB05]. This increases the diversity range, making the art of rigging difficult to master.

Inconsistency of facial movements: due to our daily basis, everyday familiarity and sensitivity to facial appearance, humans can identify and classify unnatural behavior [Mor70]. Steve Maddock stresses that the representation of facial behaviors are always more important than the display of the visual look in terms of human-like and empathy [MES05]. The difficulty lies behind the diversity of behaviors inherited from the various visual styles. A possible solution is to produce realistic behaviors using FACS (Facial Action Coding System) [EF78], but in many occasions it is necessary to combine the classic principles of animation when rigging a character [Osi07, Har05].

Lack of standard: as far as we are aware there is no rigging standard. However, the MPEG-4 is a standard [PF02] commonly used for facial animation [VS09, Ern11] that could eventually be used for rigging. Other standards that assist the rig and animation process are FBX and Collada file formats. They can store rig and animation data to be used cross-platform. But in general artists do not follow a formal criteria or method when creating a rig, this process is intuitive, therefore all rigs might end up differently. A possible cause is the high number of software packages and in-house tools used for rigging based on their own specifications. Another possible problem is the wide range of applications (films, videogames, virtual reality, vfx) defined with a different rig architecture. As a result, it is very often that during production it is necessary to create a variety of rig templates to support different behaviors. For instance in the film *The Incredibles* (Pixar, 2004) characters with super powers had a rig that allowed squash-and-

stretch movements, while characters in the real world had a different rig limited to normal movements that obeyed the laws of physics.

Rig complexity: the inherent complexity of the human face [EF75, Fai90] along with the evolution of technological capabilities of computer graphics, in terms of animation and deformation, results in the increasing development of complex rig techniques [Orv07, O’N08, DMOB10, MAF10]. Another major problem is the tendency artists have to add many controls to handle every region of the face to reproduce the subtleties of each expression.

4.3. Rigging Softwares

To create a rig it is necessary to understand what type of software should be used, what is its function and in what context will it be applied. The softwares can be differentiated according to the application domain, the creation of the rig or its manipulation. Commercial animation packages like Autodesk Maya or NewTeck LightWave [Aut12a, Ble12, New12, Aut12c, Aut12d] commonly used in productions, provide tools for both creation and manipulation of the rig in order to achieve model animation. However, the rig real-time applications usually can only be animated interactively. A clear example of this is the video game graphics engines [Gam12, Cry12, Tec12].

During the process of rigging a character the TD has access to different tools that simplify the creation process. In general this software is proprietary of each studio and can be achieved with the animation package’s API or with scripting languages like Python. For example, these tools can be used for automatic creation of the skeleton and to control the structure of a rig (autorig) or to provide new UI features. Other specific tools can be helpful to retarget deformers and simplify the process of setting the deformers or to check different issues related to production pipeline, name-conventions, file exporting, optimizations, etc. During rig manipulation, different rigging techniques can be added in order to improve the behaviors like new deformers or transformation solvers (EJ IK solvers, constraints) (See Figure 8).

There are also specific solutions for facial animation and rigging:

Bony Face [SF12] is a plug-in for Autodesk 3dsMax [Aut12a] that automatically generates a bone based system and applies it to a character’s face. The main purpose of this system is to simulate how real facial muscles behave;

Facial Animation [Ani12] Toolset is a plug-in for Maya that is available since 2006. It was developed to rapidly create efficient and believable non-linear character facial deformations. It provides a high quality facial model and a predefined UI with controls to manipulate the movements of the character’s facial regions;

Face Machine [Anz12] is a face autorig tool in Maya

[Aut12c], based on intelligent point weighting that generates direct manipulation of the controls of the character’s facial skin;

Face Robot [Aut12b] is a tool available inside the Softimage package [Aut12d]. It aims at reducing the preparation time of facial rig by providing a step by step wizard to the facial rigging process. It uses a soft tissue solver technology that automatically creates direct manipulation controls that simulate organic facial skin movements upon manipulation. Face Robot can be used with motion capture data or via key frame animation.

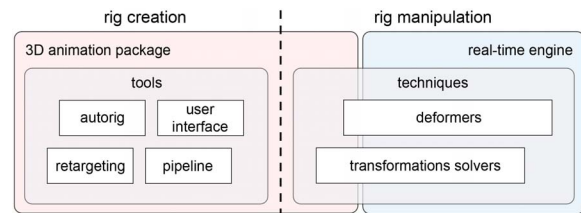


Figure 8: Left: the rig creation process occurring in a 3D animation package by means of its tools; Right: the rig manipulation process occurring in real-time through transformation and deformation manipulation techniques.

5. Morphologies

Before understanding facial movements, it is necessary to analyze the shape and structure of the geometry. The study of the facial morphology provides the facial features needed for the design of its rig structure. There are two types of morphology requirements: *taxonomic* and *geometric*. The first one describes the shape of the anatomy and the visual styling of the face. The second one defines the type and geometric techniques that can be applied for shaping the 3D model.

5.1. Taxonomic Morphologies

One of the biggest problems of representing a face is due to their anatomical diversity and to the variety of visual styles, turning harder to reproduce an empathic and human-like face. Many authors [Mil04, Gor05b, MG06, MS07, San07, O’N08, DS10] mention that before starting to rig a character, it is important to understand both human anatomy and comparative anatomy.

The anatomic diversity is a well-known problem, therefore authors define the face structure of a realistic character in an anatomical [Gra74, O’M83, Pes12], anthropometric [FL94], and artistic form [Par03]. The difficulty of comprehending the morphology of the face increases when artists introduce concepts of cartoons or stylized faces in the 3D representation [TJ81, Las87, Bla96, Wil01, Gor05a].

Due to the variety of forms that a face can produce, in visual terms, authors may attempt to create a method for classifying styles. But there is no formal classification. The comic

book artist, Scott McCloud [McC93], proposed a triangular area that describes the *pictorial vocabulary* of the visual arts. The vertices of the triangle represent a style: (i) reality, (ii) language or simplification of the reality (like cartoon style) and (iii) the picture plane or the amount of abstraction of the face shape. A wide number of face styles can be described with this method. McCloud gives examples of facial styling that depend on the position in the triangle (see Figure 9).

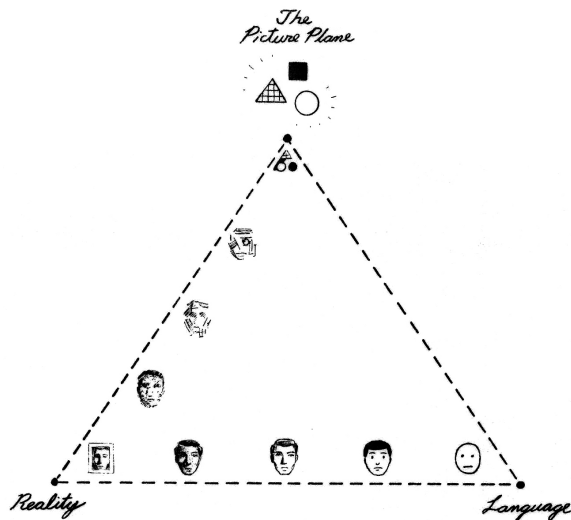


Figure 9: The Pictorial Vocabulary (McCloud [McC93]).

In the 3D domain, Ritchie et al. [RCB05], define three different facial styles. (i) Hyper-realistic, something that looks realistic and fantastic at the same time, (ii) Photorealistic, designated by the authors as *no-style* and (iii) Highly Stylized, character that can range in size and shape regardless of the limitations of the physical world. McLaughlin et al. [McL06] divide the visual style of a character in three ways: (i) Primitive, associated to cartoon aesthetic. (ii) Abstract, the process of turning an element into a new form, description of characters whose forms are composed of physical plausible elements. (iii) Naturalistic, when the character looks and behave exactly like a creature or person in the real world. Figure 10 shows a comparison between artists taxonomy.

5.2. Geometric morphologies

Geometric reconstruction of 3D facial models [Par72, PZV05, SKSS06, BBB*10, EU07, KSAR10, DSWH07, CH08, WD08] has been an object of research for nearly four decades, and the production modeling techniques [Una04, UG05, Osi07, Oli07, FSS*07, Pat08] are well known in the industry. In terms of rig, defining the geometry like an output to the deformation, requires the study of geometric representation techniques.

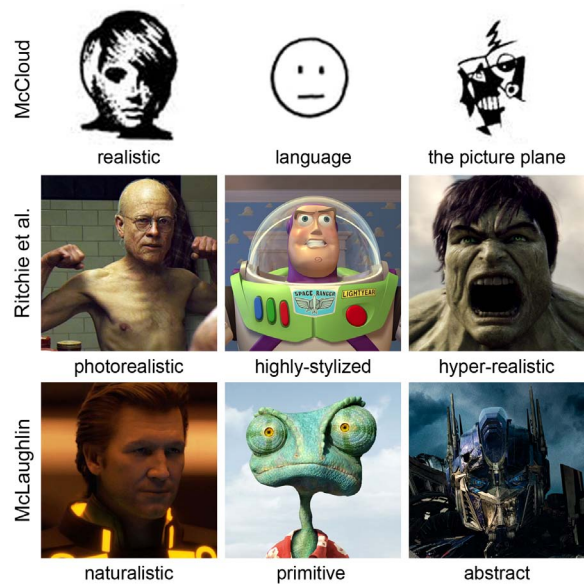


Figure 10: Classification of different character facial styles. Groups of taxonomic morphologies. Top row: early concepts by McCloud; Middle row: somehow recent concepts by Ritchie et al. [RCB05] (from left to right: Benjamin Button, Toy Story and Hulk); Bottom: most recent concepts by McLaughlin (from left to right: Tron Legacy, Rango and Transformers)

Geometric representation involves using polygons, NURBS (Non-Uniform Rational B-splines) or subdivision surfaces. Either of the former techniques have benefits and limitations that depend on the context of where the rig is being used. Figure 11 illustrates three facial models each one with a different geometric representation.

Today polygons are the most popular geometric representation approach to model a character's face [Oli07, Pat08, WD07, FSS*07]. The earliest attempt to determine the minimum number of polygons needed to model a realistic face established the use of 250 polygons [Par72, Par74]. This number has been gradually increasing ever since, because of the greater demand for higher quality in the facial model and due to the evolution of computer graphics hardware. NURBS emerged in the early 70s from the work on curves and surfaces of Pierre Bézier. In the mid 90s DeRose et al. [DKT98] point that "the most common way to model complex smooth surfaces such as those encountered in human character animation is by using a patchwork of trimmed NURBS", included in existing commercial softwares such as Alias-Wavefront and SoftImage. In the late 70s Catmull et al. introduces the subdivision surfaces technique [CC78], but is in 1997, with Pixar short film *Geri's Game* when the subdivision surfaces were presented like a technique for facial

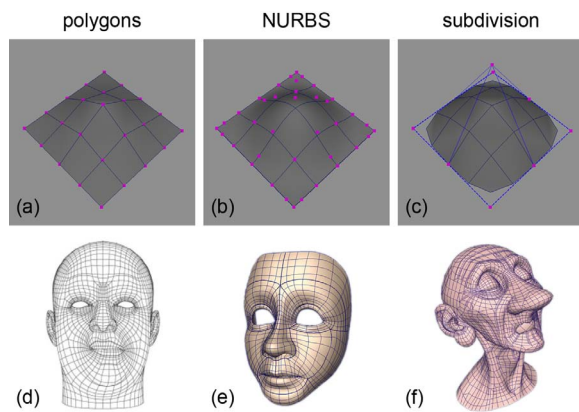


Figure 11: Types of geometries used for facial modeling: (a) polygonal, (b) NURBS, (c) subdivision, (d) Jason Osipa's polygonal human face (2010), (e) Balloon girl from short film *Bingo the Clown* (Chris Landreth 1998). Modeled in NURBS patches face, (f) Pixar's *Gerl's Game* (Jan Pinkava 1997) main character modeled with subdivision surface.

modeling [DKT98]. In fact, subdivision surfaces give better control of texturing, creases and local sharpness [Cho04].

Another important requirement concerns the topology distribution of the geometry, regardless of the employed technique. Edge loop techniques applied on the face tries to optimize the distribution of the mesh in order to perform the deformation, usually based on an anatomical approach. Waters [Wat87] made the first reference to that concept, describing that the “facial parameterization techniques have dealt principally with the surface characteristics of the skin and have not been concerned with the motivators of the dynamics”. Lately, other artists [GD05, UG05, Cab08, Par08, PW08] agree that edge loops of the facial model should be constructed according to the flow and effect of the muscle lines. This helps to maintain their location in the face and provide a more realistic animation, because the movement of the deformation will follow along the path of the muscles (See Figure 12).

6. Behaviors

This section analyzes the behaviors and the application techniques necessary to achieve a rig design. To create the rig the primary step is to understand the several layers that compose the model to recreate the expressivity of the facial poses. It is also necessary to realize the different computer animation techniques that can be applied to mimic the anthropomorphic deformation. To recreate the facial behaviors in a CG character the following layers are needed: (i) types of input data, (ii) the user interface for rig manipulation, (iii) and the deformation techniques.

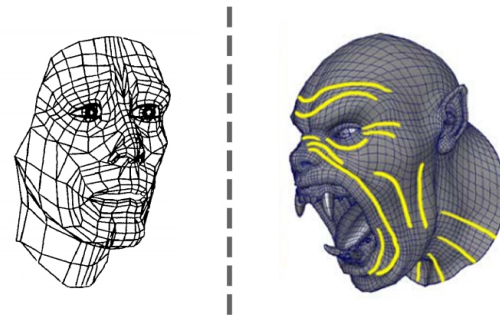


Figure 12: Geometry topology distribution. Left: first edge loop representation [Wat87]; Right: current state of the art on edge loop representation [UG05].

6.1. Facial Behavior Requirements

One of the first references of facial behavior can be found in the Charles Darwin's book *The Expression of the Emotions in Men and Animals*. This book can be considered as a starting point to study behavioral expressions of the face [Dar72]. Later in the mid 1970s, Ekman and Friesen [EF75] identified the six basic facial expressions: surprise, fear, disgust, anger, happiness and sadness. Soon after unraveling the main facial expressions, Ekman and Friesen [EF78] created FACS, the Facial Action Coding System. FACS is a manual that recognizes, describes and scores the muscular activity of the human face into Action Units (AUs), Action Descriptors (ADs) and Gross Behavior Codes (GBCs). It comprises the visible facial movements that produce momentary changes in facial appearance (either emotional or conversational signals). It is the largest and most accurate reference available regarding the study of the human facial behaviors. Therefore, FACS is a reliable reference to determine the categories in which to fit each facial behavior, without having to recognize what facial muscles are responsible for what movement. Many authors support their work with FACS [Per97, Mil04, RCB05, EH07, ARL*09, VS09, Ath10, LWP10, KMML10, Osi10, Arg11, MCC11, WBLP11].

The Artist's Complete Guide to Facial Expression, a book by textitFaigin [Fai90], is also a comprehensive visual index of the facial actions. The book is supported with detailed illustrations of the role of the facial muscles, the nature of their motion and the effects of their movement on the facial skin.

Pandzic and Forchheimer [PF02] describe the MPEG-4 facial animation specification, the first facial control parameterization to be standardized. Since then, the MPEG-4 facial animation standard has been used in the entertainment industry, medicine and telecommunication. It defines animation independently from the facial model, provided that the model is properly annotated according to the standard. It is based in three types of facial data: facial animation parameters (FAPs), facial definition parameters (FDPs) and the

FAPs interpolation table (FIT). FAPs are the minimum set of parameters that MPEG-4 established for facial animation. This includes 84 feature points (FPs) distributed on a number of base key frames of a standard facial model posed in a neutral expression to easily reproduce facial movements, expressions, emotions and speech.

These requirements are mainly used to create realistic facial behavioral models. However, in simultaneous animators introduced de cartoon animation concepts for the face [TJ81]. For instance, Blair [Bla96] defines expressions, acting and lip-sync concepts for cartoon facial animation. While the introduction of the traditional concept of animation in CG [Las87] artists reproduce the techniques for CG cartoon facial animation [Osi10, Har05].

6.2. Motion Data

In order to understand the rig as a motion data converter of geometric deformation, first we need to define the *input motion data*. Schleifer [Sch10] proposed three inputs of motion to the skinning system that, depending on the rig, can be mixed: *keyframe animation*, *motion capture* and *procedural animation*.

Keyframe animation continues to be popular in CGI animation features. The term keyframing was introduced in computer graphics in the 70s [BW70]. Kochanek and Bartels introduced the use of splines that interpolates a set of spatial control points and allow temporal control by editing high-level parameters at each control point [KB84]. Later, the technique was applied to skeleton structures [BW76]. Lasseter [Las87] introduces the principles of traditional animation into 3D keyframe animation and Reeves et. al. presented The Menv [ROL90], an animation environment that uses editable spline curves of single animation parameters per time (e.g. still widely used x translation, z rotation). Their animation graphical editor is included in current commercialized softwares. In 1995, Snibbe [Sni95] introduced motion path as a solution for editing keyframe animation in 3D, by splitting the parameters into 3D position and time, allowing the direct control of the positions.

Until now keyframe techniques remain the same. Its application on facial animation depends on the artist's skills and on the design of the facial rig.

The importance of **motion capture** techniques have been increasing in the industry business. In general terms, these techniques are referred by Menache [Men11]. Motion capture (or facial performance-driven) can be achieved by using two methods: *image tracking* and *geometric acquisition*.

The advances accomplished by [Wat87, LTW93, LTW95], made it possible to digitize facial geometry using scanning range sensors, to create a structure facial mesh and to animate it through the dynamic simulation of facial tissues and muscles. This led to further research related to motion esti-

mation from video. Williams [Wi90] introduced the first approach where he presented a method for tracking and acquiring facial expressions of human faces from a video stream. He also applied the extracted data to computed generated faces.

Most of the methods allow tracking facial markers set on an actor, recover 2D or 3D positions of the markers and animate the rig using the captured data (streamed or stored). In order to avoid manual tweaking or the application of re-targeting techniques [NN01, Orv07, DMOB10], motion capture methods demand that the performer's face resembles as close as possible the target's face, preventing the need to correctly map the movements of the rig [FNK*00, CXH03]. The development of a variety of markerless motion capture systems [BBPV03] and facial feature tracking from videos, using complex models, [RE01, HIWA05] was due to marker-based systems' limitations.

Facial mocap techniques are combined with blend shapes (Section 6.3.2) [DCFN06, LD08] to provide artists the possibility to locally control animations. Quing and Deng [DCFN06] used PCAs to modify the blendshape weights, while Den et. al. [LD08] used Radial Basis Function (RBF) and manually tune the weights of the blendshapes.

Recently, Beeler et. al. [BHB*11] presented a performance-driven markerless facial capture system that uses high resolution per-frame geometry acquisition using stereo geometry reconstruction, even though their approach does not include any concept directly related to rigging, it would be interesting to explore it. Also in 2011 Huang et. al. [HCTW11] introduced a new approach that combines motion capture data with a minimal set of face scans in a blend shape interpolation framework, which allows the reconstruction of high-fidelity 3D facial performances. In a more practical way, Weise et. al. [WBLP11] described a real time method for animating a face using tracking algorithm that combines 3D geometry and 2D texture registration to achieve motion to a rig based on blend shapes.

In terms of behavioral movements, procedural animation for the face is a not very explored area. There are some examples of these kind of technique, such as [Per97] that introduced a real time system to make autonomous facial animation of moods setting parameters. [AD07] introduces a procedural method of facial animation based on FACS using agents with three interacting parameter spaces: knowledge, personality and mood. [QCM09] developed a framework for facial animation with behavioral expressions, lip-sync using a MPEG-4 parameterization.

6.3. Rig

Rigging a face model has attracted much attention in recent years. To keep the size of this section manageable and due to

the extensive available bibliography related to facial animation, the material presented is restricted to topics that only focus on facial rigging.

We start by giving an overview of the differences between the face and the body. By face is understood as a surface of the front of the head's character from the top of the forehead to the base of the chin and from ear to ear that sometime can include the neck and the Adam's apple.

Research on body animation has influenced in a great manner facial animation. These two are entitled to the same issues: muscle deformation, soft tissue deformation and animation retargeting. But they also differ in a great manner: the number of muscles necessary to create a facial expression is larger than the muscles necessary to create a pose for a particular part of the body. In facial animation the head cannot be animated with only one joint as most parts of the body. The soft tissues simulation needs to be more realistic in order to capture all the details and subtleties of an expression. Another difference is due to the impossibility of the animator to achieve a realistic result, overcoming the expectations of the observer, who is an expert in detecting expressions. The smallest anomaly in the face shape, proportion, skin texture or movement is immediately detected and classified as incorrect. This is known as the *Uncanny Valley*, introduced by [Mor70, HOPA05] (see Figure 13).

In order to obtain a lifelike response, facial animation requires more work than body animation, because it needs to use more variety of deformer to simulate the soft tissue and muscles, designate more joints to influence each region of the face and implement more controls to manipulate the entire head structures and secondary face regions. As stated by Kahler, "Every face is unique - in its looks, its shape and proportions, as well as in the specific ways of articulation and expression that are so characteristic for an individual" [Kah03]. The main goal is to offer the artist the capability of adapting the face model to the uniqueness of each character with a very sophisticated facial rig.

6.3.1. User Interface

In order to produce movement, the animator or performer has to understand the rig as a structure that needs to be manipulated. The rig's user interface (UI) can be defined as a layer of controls that allows user interaction. This interaction can be achieved with hardware devices (like motion capture) or software based on UI. The UI rig definition can be understood as a solution within the rig's system software. Hardware-based system is not part of the rig. It is considered as an external entity that provides input data.

Wintkin and Kass introduced the concept of high-level control interface for keyframe animation for a character [WK88]. While, Conner et. al. [CSH*92] and Strauss and Carey [SC92] introduced the notion of widgets to be used as a direct manipulation interface in 3D that was later adopted

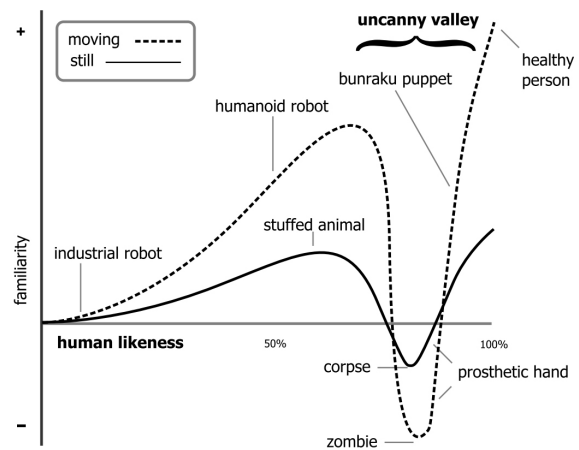


Figure 13: *The Uncanny Valley hypothesis, introduced in a study of the emotional response of humans to robots, revealed that human response positively increases as the appearance of non-human entities becomes more humanlike, until a certain point where the response quickly becomes strongly repulsive. The closer the appearance and motion of these entities gets to a human being, sometimes undistinguishable, the faster the emotional response and familiarity reaches human to human empathy levels. The gap of repulsive response stimulated by the "almost human" entity is called the Uncanny Valley. (Original graph by Dr. Mori 1982)*

by commercial packages. In fact, there are a large amount of different approaches to the UI for rigging, but essentially it can be resumed in two domains that can also be combined: (i) *window-based* and (ii) *3D viewport*.

Window-base UI provides direct input of values in a variety of forms, such as Villagrasa and Susin [VS09] that presented a slider-based UI based on FACS. Holly [Hol06] proposed to build an UI in a separate window with buttons and sliders that ease the selection and modification of the controls located in the surface of the facial model. Bredow et al. [BSK*07] took advantage of Maya's channel box and configured it to display multiple categorized columns of attributes.

In the *3D viewport* UI it is common to use 3D objects as a control to manipulate a rig. Authors like [Osi07, Nea08] propose a set of 2D controls constrained to a square, visible from the viewport, that drives opposite behaviors in each 2D axis to accurately identify the facial movements. The Digital Emily Project [ARL*09] used the same technique of a 2D constrained space, but with an anthropomorphic shape control. Komorowski [KMML10] presents a viewport UI where controls can be linked to the face behaviors with a 3D space volume. Other artists combine high level controls to manipulate major muscular groups, usually called macro-controls,

and low level controls for subtle movements, usually called micro-controls [Hol06] (See Figure 14).

Other UI approaches [LA10,SILN11] introduce the possibility of manipulating a rig with great amount of blend shape targets in a 3D space by using direct manipulation interfaces.

Sketching techniques have also been used as UI control systems. Nataneli and Faloutsos [NF06] introduced a method based on sketch classification to activate the blend shapes. Chang and Jenkins [CJ07] developed a deformation method that deforms geometry based on two sketched curves. A recent system presented by Miranda et. al. [MAO*11] shows how it is possible to simplify the control interface by allowing direct manipulation of the rig by sketching on a 2D canvas or directly over the 3D mesh.

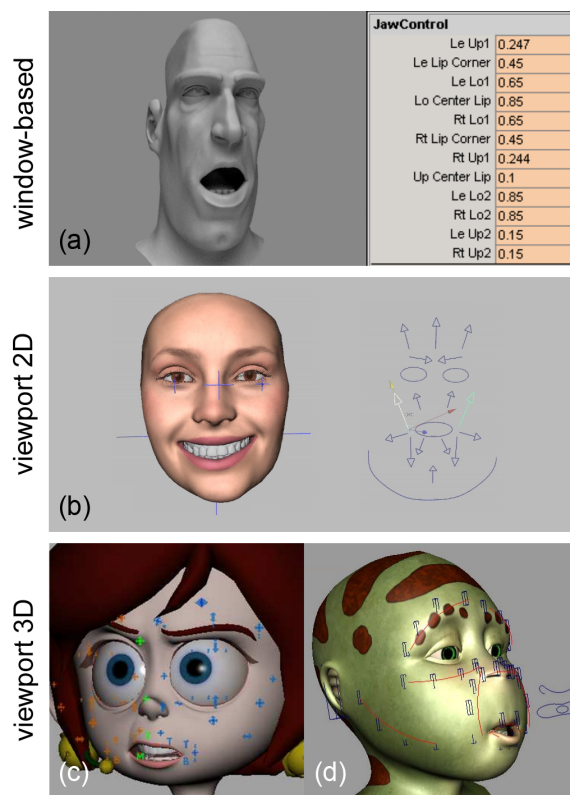


Figure 14: Example of window-based UI by Scheleifer [SSMCP02]; Example of viewport 2D controls by Alexander et al. [ARL*09]; example of viewport 2D controls by komoroski et al. [KMML10] and by Grubb [Gru09]

6.3.2. Transformation Structure and Deformers

The creation of a rig is mostly based on *blend shapes* or *bones-based* techniques. Independent of these approaches, an additional layer of deformation can be added, emphasizing different facial features, such as wrinkles, in areas of the

face where neither bones nor shapes produce the desired results. These deformer are divided in two groups: the *free-form deformer* and *physically-based methods*. In addition it is possible to combine all of the above, Figure 15 exemplifies them.

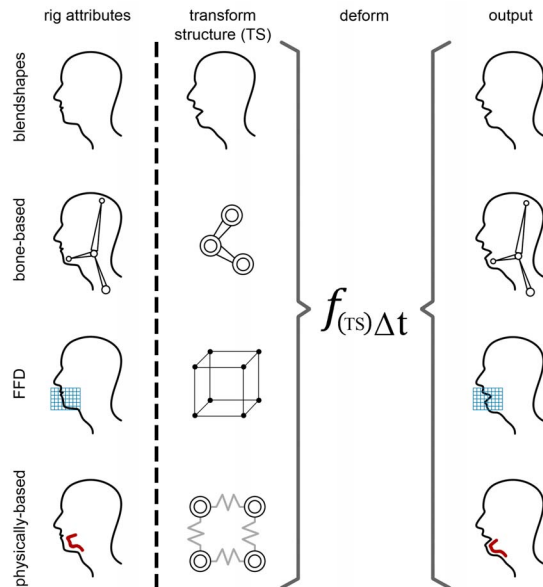


Figure 15: Different approaches to face deformation: Blend shape, Bone-based, FFD and physically based.

Blend shape. Parke [Par72] introduced the concept of geometric interpolation in the animation of the face, but the short film *Tony de Peltrie* [BL85] popularized the usage of shape interpolation. Blend shape consists on sculpting facial poses into several meshes of the same topology [Mar03]. Each mesh is designated as a shape. Thus, morphing several shapes generates the character's animation. For instance, interpolating between the open mouth shape and the neutral position makes the character open or close it. It is possible to define localized shapes in each region of the face, enabling independent control of that region and allowing mixing multiple shapes to create a wide variety of poses during animation [SRC01].

A face model can be completely rigged using only blend shapes (see Figure 16). However, it is necessary to create a large number of shapes to provide control over every region of the face. Facial animation of *Gollum*, in the film *The Lord of the Rings: The Two Towers* (Weta, 2002), requires 675 blend shapes, which is an example of a complex rig fully created with blend-shapes [For03]. But it is possible to create such complex behavior and realistic facial expressions by using a smaller amount of shapes, or combining them with other animation techniques [RCB05]. Mixing shapes can limit animation accuracy and difficulty increases with the size of the region. The bigger the region to

blend, the harder it is for animators to obtain appealing results. Defining manually all of the shapes for just one model is time-consuming and needs considerable skills. This process is repetitive for each character to be animated.

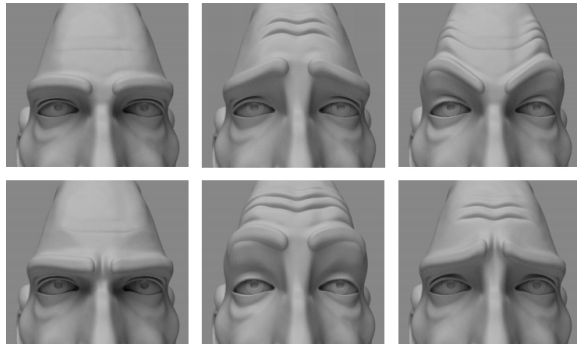


Figure 16: Example of different poses achieved with blend shape interpolation. Schleifer et al. [SSMCP02]

Blend shape is a common technique used by artists in facial animation. Osipa [Osi07] introduced a manual for producing a facial rig using blend shapes. Unay et Grossman, rigger artists, [UG05] proposed some production methodologies to create and combine shape targets.

However, blend shapes for facial rigging has some limitations in terms of modeling, mixing, control and optimization of target shape. Beeson and Bjork [BB04] proposed an implementation in GPU of the classical geometric interpolation of shapes target for facial animation. Lewis et. al. [LMDN05] presented a method to prevent artifacts and tweaking when mixing a number of different blend shapes. Joshi et. al. [JTDP06] proposed an automatic, physically-motivated segmentation of the blend shapes in smaller regions in order to achieve subtle and complex deformation of the face. Orvalho [Orv07] presented a generic deformation retarget algorithm that can be useful for creating blend shape targets from a model rig, in order to solve the shape target modeling process. Later Li et. al. [LWP10] proposed another method of retargeting, specific for facial blend shapes. The method introduced a framework that automatically creates optimal blend shapes from a set of example poses of a digital face model. This method allows transferring expressions from a generic source model into another blend shape model.

When the model complexity increases, the manipulation of a large numbers of blend shapes becomes a problem. Lewis and Anjyo [LA10] proposed a method for their direct manipulation compatible with existing blend shape techniques. Later Seo et. al. [SILN11] extended the previous method to control efficiently and intuitively a large number of facial blend shapes with a hardware-accelerated optimization.

Other authors like Liu et. al. [LXFW11] explored the non-

linear relationship of blend shape facial animation from captured facial expressions.

Bone-based rig. The highly articulated facial skeleton structure is the base for a bone-driven rig. In spite of needing more preparation to get the desired results, this approach enables smoother movements comparing to blend shapes. The rigging process should be planned better because each vertex is only animated by the bones around it [War04]. The rigging process must be more intense and better prepared, because each vertex is only animated by the bones around it. Komatsu [Kom88] and Magnenat-Thalmann et. al. [MTPT88a] demonstrated human body deformation driven by an underlying skeleton.

To animate the model it is necessary to link the skeleton to the model geometry. In order to deform the geometry by the skeleton, the process of binding both is called *skinning*. Smooth and rigid skinning are two type of skinning technique [LCA05, YZ06]. During this process the most important task is the weight definition [WP02] that defines the degree of influence of a vertex during deformation. Then, each bone has its own distribution map that defines the amount of influence they will exert on the model during animation. Normally bone-driven rigs are used for videogame productions, like *Uncharted 2* (Naughtydog, 2009), where they use 97 joints [DS10] to animate the characters. Figure 17 shows a bone based rig of a character in the Unreal game engine. During the representation, the skeletal structure was able to reproduce basic expressions like blinking, smiling, eye gazing and phonemes. In *Uncharted 2* the animation was driven by motion capture based on the performance of an actor, each bone of the rig representing a motion sensor placed on the face.

From an artistic point of view the first step to create a bone-based rig consists in defining the skeletal structure and placing the articulation points, the joints and bones [McK06, MS07, MCC11]. Second, the rigger aligns the bones to guarantee their correct rotation during motion. Third, she attaches the character's model to an underlying skeleton, skinning. This process defines the amount of influence that each joint and deformable object will exert on the model during animation [MG03, LCA05, YZ06, MS07]. The last step involves testing the response of the rig to the manipulation of the animation controls [RCB05], which means generating keyframes for the character's rig controls [O'N08] that result on an animated model.

Geometric Deformation. In a rig, geometry deformation rigging consists in using simple operators that allow the manipulation of complex models. These operators are efficient for animating complex geometry, since they provide a high level, and simpler, interface to the deformations.

One of the most commonly used operators is the Free-Form Deformer (FFD). A FFD is a parametric solid or 3D lattice that encompasses the geometry, like a volumetric envelope and was first introduced by [SP86]. Chadwick et.

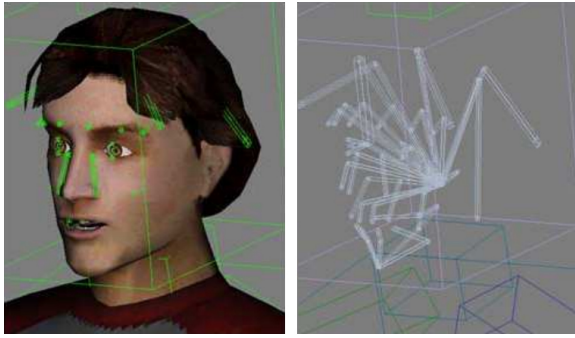


Figure 17: A highly articulated facial skeleton model prepared to be used with the Unreal game engine (Copyright 2001-2007 Epic Games)

al. [CHP89] applied the concept of free-form deformers to animate a layered character. The layered character consisted of a behavior layer, a skeleton layer, a muscle and fatty tissue layer and a surface description. This work can be considered as one of the firsts to use a hierarchical approach to animation.

In order to control the facial animation, [KMTT92] extended the concept of FFDs to Rational Free-Form Deformers (RFFD), in which weight can be assigned to each point of the parametric envelope. This addition grants a better control over the geometry deformation. The development reaches further proportions, dividing the face in regions and assigning a RFFD to each of these regions. This process allows a more accurate and independent control of the areas of the face. These same RFFDs were then used by Noh et al. [NFN00] to create a smooth animation procedure for geometry facial models. Later on, Luo and Gabrielova [LG06] developed a special type of FFDs called Dirichlet Free-Form Deformers (DFFD). DFFDs use data interpolation based on Dirichlet/Voronoi diagrams and allows the removal of the constraints of the control lattice, giving more freedom over the deformation. In this particular case, DFFDs were used to model a 3D face from a pair of input images, by a number of control points. Since these points change the geometry of the face, they can also act as a rig to control the facial appearance.

Not directly connected to FFDs, but can be used to emulate these, is the work of Singh and Fiume [SF98], in which wires give definition and shape to a model. Each wire is a parametric curve, which controls the appearance of a part of the model. By using the parameters as a rig, different poses can be created. FFD's can also be used in combination with skinning techniques to animate 3D characters [SK00]

Employing other operators, Dubreuil and Bechmann used the D.O.G.M.A. model (Deformation Of Geometrical Model Animated) on facial animation [DB96]. With D.O.G.M.A. it is possible to define space deformations in terms of dis-



Figure 18: Examples of geometry deformations: (a) D.O.G.M.A. model applied to facial animation [DB96]; (b) the use of radial basis functions [NFN00]; (c) Dirichlet Free-Form Deformers with Voronoi diagrams [LG06]

placement constrains. The deformation can be controlled over time, making D.O.G.M.A. a four-dimensional system. Later, Lewis et al. [LCF00a] employed radial basis functions to create a pose space deformation method for facial skin and skeleton-driven animation, while Chang and Jenkins [CJ06] introduced a method for articulating and posing meshes, allowing users to control a rig on a 3D mesh with a 2D sketching interface. This approach provides artists with simple control for animations, but automating these procedures still requires further developments.

Physically-based. Physically-based animation simulates the visco-elastic properties of soft-tissues, skin and muscles, mimicking the biologic behavior of these tissues, trying to achieve more realistic animations and expressions. The main methods used for simulation are mass-springs and finite elements, which can be used separately or combined.

The first attempts to create a physically-based model were from Badler and Platt [BP81], that used a mass-spring system to simulate muscle fibers. Later, Waters [Wat87] defined three different muscles models, corresponding to the kinds of muscles acting on a face: linear, sheet and sphincter. The muscle rig was independent from the underlying skeleton, offering portability, and the skin was represented by a simple geometry. The muscles drove the skin deformation, but it was still not able to produce subtle skin deformations. Waters and Terzopoulos [WT92] extended this work by creating a three layer structure for soft-tissues, representing cutaneous tissue, subcutaneous tissue and muscle. All of these layers have different mass-spring parameters, achieving a more realistic behavior. Other early works on muscles simulation can be seen in Magnenat-Thalmann et al. [MTPT88b].

The previous model was enhanced with the inclusion of scanned data by Lee et al. [LTW95]. The model, based on real human scanning data, was later animated by muscle contraction. However, this approach made it hard to produce accurate muscles' parameters, due to the complexity of the human musculature. Later, Waters and Frisbee [WF95] created a muscle-based speech engine, emphasizing the simulation of muscles as the animations' drive, over the sim-

ulation of the surface. Along the lines of data extraction, Essa et al. [EBDP96, EP97] created a system that used optical flow to analyze facial motion, which combined with geometry information, physical and motion-based dynamic models extracted a parametric representation of each muscle group, achieving a more accurate estimation of facial motion. This model, in contrast with the above, introduced a two-dimensional finite elements model for the skin. Concerning only the lips, Basu et al. [BOP98] described a tracking and reconstruction method for human lips, based on a video stream. The model used a 3D physically-based model of the lips, trained to understand the motion of the lips. Principal components analysis (PCA) was used to reduce the degrees of freedom, allowing tracking and automatically matching human lip movements. Choe and Ko [CK05], using a 2D linear quasi-static finite elements model of the skin, which simulated the actuation of muscles on the skin, presented a system to synthesize facial expressions based on captured data. Artists were required to provide the initial state of the muscles' actuation values and this leads to poor anatomic accuracy, causing unnatural artifacts and continuous recreation of the base elements.

A major improvement towards real-time physically-based muscle animation was achieved by Kahler et al. [KHS01, KHYS02], which developed a skin deformation model influenced by muscle contractions. Besides the three layer model already depicted, muscles were also connected to a skull by a mass-spring system. Different types of muscles were simulated, along with bulging, caused by the soft-tissue nature of muscles and the intertwining of the muscles' fibers. These additions improved the quality of the physically-based animation results, and were computationally light to run in real-time.

With the increase of the computational power, new physically-based models start to emerge. Using a non-linear finite elements model, Sifakis et al. [SNF05, SSRMF06] created one of the most accurate and precise muscle-based animation system. In this model, the muscles serve as actuators on the skin and are activated by sparse facial markers. Another improvement of this model was the inclusion of external forces, due to environmental interactions like the impact of an object on the face, which modifies the behavior of the animation, hence the final look of the face. As for performance-driven animation, this model is a success, although not real-time, but it is not clear if it can be applied to non-humanlike models.

Albeit the improvements, not only simulation is a research problem when dealing with physically-based animation, but also the rigging process is an issue, in this case the definition and placement of muscles. Until recently, muscles' placement was either parametric, based on scanned data, or required a tedious and technically demanding manual process of creation and positioning. To tackle this, Aina and Zhang [AZ10] proposed an automatic system for muscle

placement based on any head model. It creates a base skull, upon which it lays the muscle and the skin soft-tissues layers, building a rig. (See Figure 19)

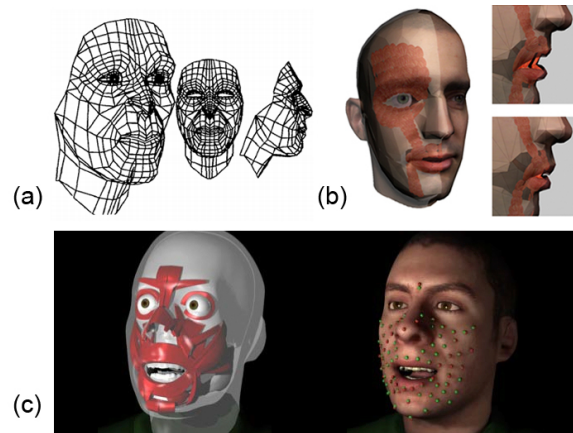


Figure 19: Examples of physically-based rigging and animation: (a) Mass-spring system for emulation of muscles fibers [BP81]; (b) Geometry-based muscles [KHS01]; (c) Finite-elements muscles and soft-tissue [SNF05]

Combining blend shapes with bone-based rigs. Budget and time is the main concern in film and videogame industry. It is very important to choose the rigging technique that better suits the project, because a rig with few joints or blend shapes makes the face look stiff and hard to control. The initial setup of a blend shape rig is simpler and is always limited by the number of available shapes. Therefore if the topology of a face is changed, all existing shapes have to be redone. On the other hand, a bone-driven rig has a complex initial set-up, guaranteeing that all desired expressions are possible, but does not need further work when the topology of the character is modified. Artists can easily define each pose perfectly with the blend shape approach, because shapes are created by hand, sculpting each vertex of the mesh. This process is not possible with a bone-driven rig, as each vertex position is influenced by the attached bones. Combining blend shapes with a skeletal approach is a common option, providing the rig with flexibility and smoothness of a bone-driven system and the expressiveness of blend shapes [LCF00b]. *Killzone 3* (Guerrilla, 2011) [Arg11] is another good example of a bone-based facial rig.

During the rigging process it is very common to go back and remodel some parts of the character [SSMCP02, UG05] to achieve better deformations or because the topology needs more resolution. This often causes the unexpected restart of the rigging process or, at least, the re-adaptation of the rig, which delays the production, especially because the rig is usually distributed into dozens of files [Hum09]. Sometimes it is even necessary to rework the rig and the controls after the animation process started because the rig is not performing exactly as the animators desired. To deal with all these

issues, the rig framework needs to be flexible, with a structure comprising the skeleton, the user interface (UI) controls and the miscellaneous controls (see Figure 20).

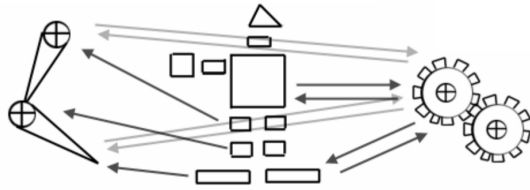


Figure 20: Basic framework of character rigging. Left: the skeleton; Middle: the UI controls; Right: the miscellaneous controls (Schleifer et al. [SSMCP02]).

For further information on the subject of facial animation and a comprehensive understanding on how rigging interfaces with the animation process, please consult the survey of Noh and Neumann [NN98] and Ersotelos and Dong [ED08]. Figure 21 shows a chronological list of significant approaches for facial rigging

7. Conclusion and Discussion

Facial rigging has come a long way since its parametric construction to modern motion capture driven control rigs. In spite of being a field of research for a considerable number of years, there are no standards for the creation and definition of a facial rig. Each studio, rigger, animator, develops its own rigging and manipulation method, while in the academia, the main interest is to push the state of the art forward, bringing new approaches and techniques to the field.

Several factors can contribute for this absence of a standard. In production, every new project has its own specificities, either with reality as gauge or with a more cartoonish inclination that require different rigging approaches, with the former requiring a control rig oriented for subtleties, while the latter employs the 12 traditional animation principles [Las87]. Furthermore, each studio has already developed in-house pipelines, which are continuously improved and entrenched working practices. This makes it hard to adopt new methodologies. On the other hand, history has already shown that the creation of standards is not always peaceful. Either the standard is naturally adopted, like in the case of OpenGL (<http://www.khronos.org>), or the standard ends up having a behemoth of features, making it practically unusable, like in the case of Collada (<http://www.collada.org>). Adding to all this, there is the fact that rigging is a mixture of science, art and craft. Improvements towards a more automatic rigging and animation, either by an automated placement of the rig control points or by the usage of facial capture, have been largely achieved. However, a considerable amount of manual work is still required from the rigger and the animator, who add a valuable asset into the production, their personal expertise.

On a higher level, taking in consideration rig manipulation user interfaces, there is also no common approach. Mostly due to the fact that the user interface derives from the underlying technology, the disparity of approaches and the work habits of each studio, lead to manipulation tools being design exclusively for each production pipeline. Some relevant work has been developed in the academia though regarding the subject of user interfaces. Sketch based and direct manipulation interfaces are taking the lead, but a one size fits all control frame, using the marionette analogy, is still to be defined. With this survey, one hopes to instill researchers and the industry to lean in a direction where a rigging standard comes into existence, and, subsequently, followed by a universal user interface.

Interesting enough is the fact that it is possible to spot trends in the field of facial rigging. The usage of facial capture and expression mapping to reproduce the subtleties of an actor's performance, in an attempt to bring more realism to the animation, is almost mandatory nowadays. Long gone are the days of a complete manual animation, but expression mapping does not come without a catch. Manual intervention is still required to clean the captured data and to best fit the animation to produce a polished and smooth result. Again, this is almost a craftsman work, with no standard approach. To tackle this, both academia and companies are researching in geometry acquisition methods that better represent the actor's performance, over the usage of markers facial capture. These methods allow, for instance, an automatic extraction of blend shapes or a rich capture of the facial subtleties.

Another trend, which can be considered almost transverse to the computer graphics field in general, is the intensification of the use of the GPU for non-rendering tasks. Considering the subject of this survey, GPU's are being use to speed the computation of the rig deformer. Although this usage in real time is perfectly natural, its application in offline production pipelines is also a reality, since it lashes product schedule times.

As a closing remark, it can be said with confidence that facial rigging has reached a mature stage of evolution, with proven methods and results. What is intriguing is that facial rigging as since then evolved in a branching fashion, without underlying conventions, methodologies or even definitions. It is most probable that the implicit analogy with marionettes and the long history of traditional animation have contributed to a general undisclosed direction. Nonetheless, facial rigging has spanned into very different branches. Some of these branches have already seized to grow, like rigging for keyframing animation, while others have sporadic developments, like the case of virtual puppeteering, which progresses in bursts of sudden interest with the introduction of new technology. Other branches are definitely spreading much apart. As an example, offline and real-time rigging methodologies have different needs and specificities. The

Year	Author(s)	Requirements										Input				Rig				
		Morphologies (by McLaughlin)					Behaviors					Keyframed	Mocap	Procedural	Geometry Acquisition	User Interface Type	Bone-based		Transform Structure/Deformers	
		Naturalistic	Primitive	Abstract	FACS	Cartoon	No Standard	Abstract	FACS	Cartoon	No Standard						Bone-based	Blendshapes	FFD	Physically-based
1996	Maestrini [Maes96]																			
2002	Georgio [Geo02]																			
	Graft et al. [EGRM02]																			
2003	Schlieler et al. [SSMCP02]																			
2003	Marani [Mar03]																			
2004	Miller [Mil04]																			
2004	Sale [Sal04]																			
2005	Gorden [Gor05b]																			
	Harkins [Har05]																			
	McKinley [McK05]																			
	Ritchie et al. [RCB05]																			
	Unay and Grossman [UG05]																			
2006	Athias [Ath06b]																			
	Chang and Jenkins [CJ06]																			
	Holly [Hol06]																			
	McKinley [McK06]																			
	Patel [Pat06]																			
2007	Bredow et al. [BSK*07]																			
	Evans and Hagedorn [EH07]																			
	Maestrini [Maes07]																			
	Mullen [Mul07]																			
	Sarsonnet [Sar07]																			
2008	Allen et al. [AMF08]																			
	Autodesk [Aut08]																			
	Clinton [Cl08]																			
	Neale [Nea08]																			
	O'Neill [ON08]																			
	Pardew [Par08]																			
	Skonicki [SK08]																			
2009	Alexander et al. [ARL*09]																			
	Alvarez [Alv09]																			
	Granberg [Gra09]																			
	Villagraza and Susin [VS09]																			
2010	Athias [Ath10a]																			
	Athias [Ath10b]																			
	Osipa [Osi10]																			
2011	Alignment [Alg11]																			
	Athias [Ath11a]																			
	Athias [Ath11b]																			
	Kazuo and Pinheiro [KP11]																			
	Vasconcelos [Vas11]																			

Figure 21: a classification table with a number of significant approaches for facial rigging

former makes use of elaborated rigs that employ different techniques, such as expression mapping, a countless number of blend shapes or muscle-based rigs, in order to achieve the best possible suspension of disbelief. The latter, due to the real-time restrictions, resorts to facial capture on top of simple joint-based rigs or minimalistic blend shapes. Curiously, there are several branches that reached out and touch each other. This is the spanning nature of facial rigging, in which the methods are not sealed and is quite common for a rigging solution to take advantage of different techniques and even fields of expertise, like the usage of blend shapes and physically-based methods.

In the end, this is probably the essence of facial rigging, with its carefully planned balance between science, art and craft, making it one of the most cross-disciplinary fields in computer graphics, with continuously open and gripping challenges.

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