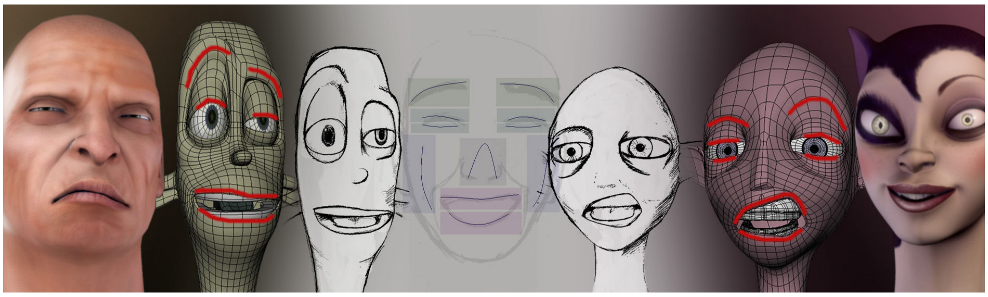
José Carlos Miranda

Intuitive Real Time Facial Interaction and Animation



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A DISSERTATION

in

Computer Graphics

Human Computer interaction

Presented to the *Faculty of Engineering of University of Porto* in Partial Fulfillment of the Requirements for the *Degree of Doctor of Philosophy*

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Porto, Janeiro 2013

This research is partially supported by:
Fundação para a Ciência e Tecnologia (SFRH/BD/46588/2008),
Instituto de Telecomunicações,
and the projects:
LIFEisGAME (ref: UTA-Est/MAI/0009/2009),
VERE (ref: 257695)
Golem (ref: 251415, FP7-PEOPLE-2009-IAPP).

Abstract

Facial Animation is the key element to express emotions in virtual characters. One of the major challenges in the entertainment industry is to ensure that the characters are highly expressive to reinforce the attention of the audience. However, creating appealing and convincing facial expressions is a laborious and time-consuming process since the representation of a 3D face is extremely complex. Animators usually work with a control structure, named *rig*, in order to simplify the manipulation of a 3D face. Nevertheless, this process requires the full understanding of the rig's structure and it also involves hard and long manual work since the artist needs to manipulate each rig's control individually. This task can be tedious and demands a lot of time to create believable results.

We propose a change of paradigm in the way a rig is controlled. The method developed in this research allows to manipulate a rig structure through free-hand drawing. It enables to handle a large number of rig's controls at the same time, through a single stroke drawn on the user interface. As several rig controls are encapsulated in just one control curve, which is generated by the drawn stroke, it is possible to create rapidly complex deformations with just a single and continuous movement of the hand. This thesis presents a facial sketching control method, which is designed to reduce the time and effort necessary to create facial expressions. Inspired in the way people draw, our approach allows the user to sketch simple strokes which define the shape of the deformation. These strokes can be drawn either directly on the 3D mesh or on a virtual canvas, resulting in the deformation of the 3D face.

Our system was validated with a series of experiments. We highlight that the sketching paradigm: (1) is simple and fast to create facial expressions (2-4 minutes), even without any previous training; (2) requires a shorter learning

curve when compared to traditional rigging techniques. The results were supervised by Technical and Art Directors, who approved the quality of the created facial expressions. This is a crucial outcome for the system to be used in CG productions. As a result, it significantly improves the production workflow, since it speeds up the creation of facial expressions through an intuitive sketch-based interaction model.

Resumo

As indústrias do cinema e dos videojogos têm sofrido um forte crescimento nos últimos anos. A necessidade de animar personagens virtuais que consigam captar o interesse do espectador tornou-se um dos maiores desafios da indústria do entretenimento. Um dos aspectos mais relevantes na animação de personagens 3D é a manifestação de emoções através da expressão facial. No entanto, criar expressões faciais convincentes e apelativas é um processo moroso, uma vez que a face é composta por inúmeros detalhes que tornam a sua manipulação extremamente complexa. De forma a simplificar a manipulação de uma face, os artistas usam normalmente uma estrutura de controlo, conhecida por *rig*. Mas, controlar um *rig* implica o total conhecimento da sua estrutura interna e envolve um extenso trabalho manual, uma vez que o artista necessita manipular os elementos do *rig* de forma individual. Este modo descontínuo de controlar um elemento de cada vez requer muito tempo para criar deformações faciais credíveis.

Nós propomos uma mudança de paradigma na forma de controlar o *rig*. O método desenvolvido nesta investigação permite, sem qualquer necessidade de conhecimento da estrutura interna do *rig*, a manipulação de um grande número dos seus elementos em simultâneo. Através do desenho de uma simples curva, de um gesto contínuo, é agora possível criar deformações complexas de uma forma célere. Esta tese apresenta um sistema intuitivo de controlo facial, concebido para reduzir o tempo e esforço necessários à criação de expressões faciais. Inspirada na forma como os artistas desenham, a nossa abordagem permite ao utilizador, através de simples curvas, desenhar a forma da deformação. Estas curvas podem ser desenhadas directamente sobre o modelo 3D ou numa área de desenho bidimensional, denominada por *canvas*, resultando na deformação da face 3D.

O sistema desenvolvido foi validado com uma série de testes. Importa realçar que : (1) o sistema é simples e rápido na criação de expressões faciais (2-4 minutos), sem qualquer treino prévio; (2) o sistema apresenta uma curva de aprendizagem mais rápida do que as técnicas tradicionais de *rigging*. Os resultados foram supervisionados por profissionais da Indústria, que aprovaram a qualidade das expressões faciais criadas através do método desenvolvido. Este resultado é crucial para o sistema poder ser usado em produções profissionais.

Acknowledgements

I would specially like to thank my professor Verónica Orvalho for her help and dedication in this long journey. From the start, her extremely pleasant attitude and knowledge in the area of facial animation were most encouraging and motivating. It was great to work with a person like her. I would also like to thank my professor Augusto de Sousa for his advices and friendly support.

I am specially grateful to Xenxo Alvarez, who dedicated many hours to provide me with high quality test material. His constant feedback contributed greatly to improve the system. I extend my thanks to Andrew Tucker for the cartoon models.

Irina and José Soleno from Digital Animation School at University VERITAS, Costa Rica, for the enthusiasm with which agreed to participate in the validation process as well as the commitment and professionalism shown when conducting the experiment.

My colleagues Miguel Salgado and Paulo Vieira for their unconditional support in the statistical validation.

I specially thank Carla Martins and Jacqueline Fernandes for the text revision.

To all my lab colleagues who helped me with thoughts and comments during the development of my research.

To all my professors of PRODEI (FEUP), for their teachings.

Finally, I want to thank my family and all my friends for their willingness to listen to my formulations about my ongoing research, for their support and their understanding. Special thanks should go to my parents, always available and happy for my arrival in Oporto and for their constant worry about my education. Most of all, I ultimately want to thank Anita and my handsome son Sebastião for their unconditional love, their numerous sacrifices, understanding and their support over the last five years.

Now, I am back!

To my son Sebasti

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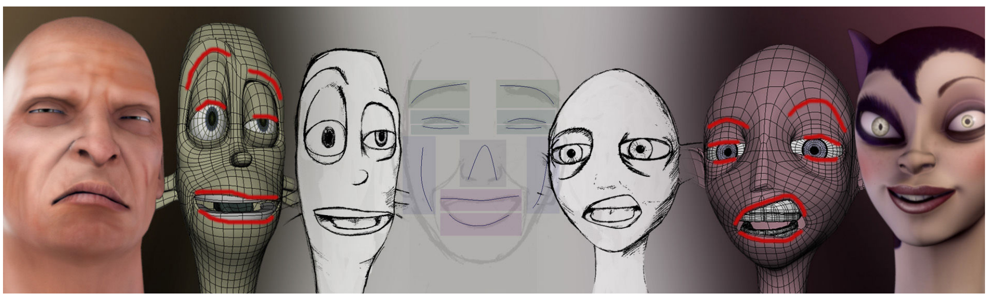
Chapter 1

Introduction

Facial animation has been an area of intensive research for the last four decades [Parke 1972] and it is currently in great demand. The entertainment industry is the main driver for the development of advanced computer facial animation systems. The increasing number of computer generated (CG) films and videogames require more and more sophisticated characters performing complex facial expressions. The character's face plays a crucial role to keep the involvement and interest of the spectator. We studied techniques from the fields of computer graphics and human computer interaction, to come up with an approach that speeds up the process of creating complex 3D facial deformations. We propose a facial sketching control system *inspired in the way artists draw, where a stroke defines the shape of an object and reflects the user's intention. The method proposed in this research deals with the manipulation of a facial rig. This chapter briefly describes the motivation of our research, gives an overview of the proposed method and summarizes the contribution of this dissertation.*



1.1 Motivation

The face performs an important role in verbal and non-verbal communication for humans and 3D characters, but the representation of a face in 3D characters is complex. A face can express a variety of visual styles (from realistic to cartoonish) and to produce a multitude of facial movements. As there is no formal method for classifying character's styles it is a challenge to represent a 3D face [Orvalho et al. 2012]. The representation of a face becomes more complex when working with 3D human faces since the simulation of all the details like muscles, bones and wrinkles are necessary. These details' simulation must follow anatomic movements in order to show all the subtleties of a facial expression. Moreover, it is not easy to achieve realistic results and overcome the expectations of human observers, who are experts at watching faces, because any inconsistency in a face detail is easily detected. Therefore, generating an appealing facial animation is laborious and time-consuming.

The oldest method to animate 3D models is based on *keyframe* techniques. These techniques interpolate all the vertex positions of a 3D model in a given period of time. However, when the complexity of the model increases, editing each vertex of the mesh quickly becomes impracticable. Thus, it is fundamental to create a simplified structure to control the 3D model. Luxo Jr. [Pixar 1986] was the first to introduce a control technique to manipulate a desk lamp *articulated structure*, instead of editing each vertex of the model. Since then, advances in animation control techniques gave origin to what we know today as *rig* [Magnenat-Thalmann et al. 1988a]. However, it was only in the 90s that the rigging concept emerged due to the increasing need to have characters performing complex actions. Toy Story [Porter 1997] is the first CG film bringing the principles of classic animation [Lasseter 1987] and rig concepts into a 3D production. Nowadays, rigged models are generally used by animators.

We can loosely define a generalized rig as a structured set of elements that can modify an associated geometry by manipulating a set of controls in a User Interface (UI). The rig can range from a simple bone system to a more sophisticated hierarchy of elements (blendshapes, wire, lattice, constraints). As the complexity of the rig increases, creating the required different poses of the model by hand quickly becomes impractical. Thus, mastering the manipulation of rigs in a short period of time is challenging for artists and almost impossible for non-experts. User interfaces associated to the rig provide high-level controls, masking most of the technical difficulties of the animation process. It eases the rig manipulation, thus helping the artist to focus on the creative issues. While high-level rigs can simplify the animation process, encapsulating a set of rig elements on a single control object presents a particularly challenging problem:

to design an interface that intuitively maps the manipulation of the control object to the model deformation, while increases the rig usability.

1.2 Method Overview

We focus our research on the design and definition of a rigging control method for the manipulation of 3D characters for films and videogames. The overall goal of this thesis is to define complex 3D deformations with just a free-hand drawing. We propose a *facial sketching control system* based on simple strokes drawn on a 3D mesh or on a virtual canvas (see Figure 1.1).

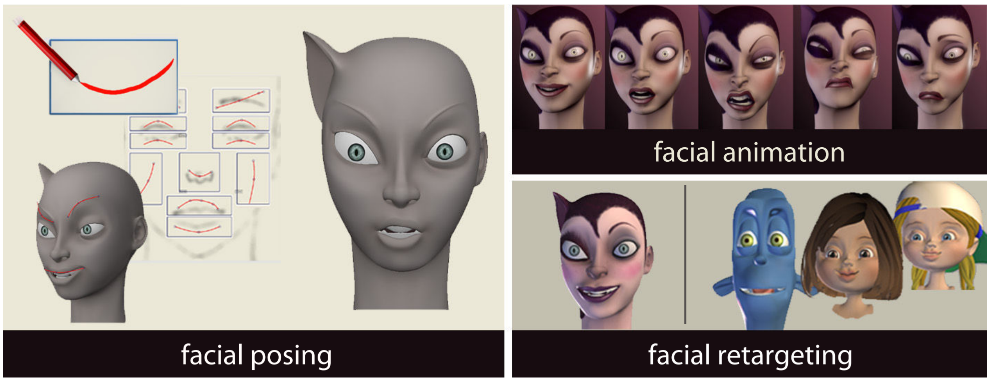


Figure 1.1: Facial Sketching Control System Overview. left: the artist can draw strokes directly on the 3D mesh or on a virtual canvas to create facial poses; right up: the created poses can be used to generate facial animation; right down: one facial pose transferred from the cat-woman character to different target characters.

Sketching is an increasingly popular way to create, deform or control 3D models. However, while most of the sketching approaches act directly on the 3D mesh of the model, the proposed method should act on the rig of the model. The innovation of our work lies in the manipulation of the underlying rig's structure, instead in the manipulation of the mesh's vertices.

We propose a change of paradigm in the way a rig is controlled. In most of traditional approaches, the elements of the rig are controlled individually (one by one), in a discontinuous way. In the proposed method it is permitted to control a rig in a continuous way: a user can manipulate several elements of the rig at the same time, using just one stroke. This enables the fast creation of complex deformations by using just a single hand continuous movement. Despite the loss of precision, which usually is associated to the sketch-based interfaces, in the proposed approach the quality of the deformations will be constrained by the rig.

Furthermore, it becomes possible for the user to control an object without the understanding of rig's structure of the correspondent 3D model, so it will permit intuitively to create facial poses from scratch without manipulating complex rigs. As a result, rapid animation in real time will be performed by sketching strokes directly on the 3D mesh or on a virtual canvas. Additionally, the created poses can be automatically transferred to different models by storing the 2D strokes, so they can be reused in different models.

The hypothesis of this research intends to prove that:
using a continuous sketching interaction, it is possible to simplify the rig control process, in order to generate complex deformations on any 3D face, in real time.

We illustrate the method proposed in this thesis with two implementations: one for artistic purposes embedded in the software Maya [1] and the other for learning in therapeutic purposes, developed as a stand-alone application (see Figure 1.2). We used several facial models of distinct artistic styles, from photorealistic to cartoon, and, additionally, we have carried out several experiments with artists. The user study shows that users can create appealing 3D facial expressions in just a few minutes, without previous training. The facial poses were instantly transferred to other characters with 82% of accuracy due to the new retargeting method developed.

[1] http://usa.autodesk.com/maya/

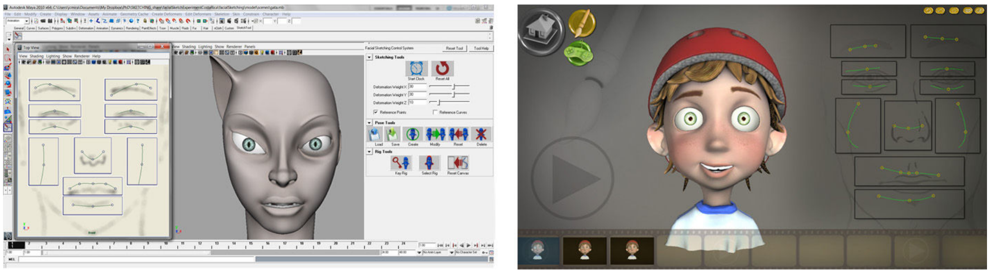


Figure 1.2: Two different implementations of the sketching control method; left: Maya plugin for artistic purposes; right: LifeIsGame, a learning system for therapeutic purposes.

1.3 Main Contributions

The key contributions of this dissertation to the field of *Computer Graphics* and *Human Computer Interaction* are:

- a **facial sketching control method** to manipulate a rig structure through free-hand drawing; it allows to manipulate, in a continuous way, a large number of rig elements and, as a consequence, to create complex 3D deformations by a single control curve: the stroke;
- a **depth constraint method** to work on the top of the rig; it automates the movement of the rig elements on the Z-axis, which automatically maps the deformation from 2D to 3D;
- a **retargeting method** to transfer facial expressions between 3D characters; it allows to reuse the same strokes in different models to generate facial poses.

As a result, our *facial sketching system* can impact the film and videogame industries. It can be integrated into existing animation production pipelines and significantly improve the workflow, as it speeds up the creation of facial poses through an intuitive and interactive sketching method. Furthermore, the results from our project can benefit other areas where the face plays an important role in visual communication, such as psychotherapy, broadcasting, criminology, virtual worlds and others.

1.4 Outline

The remaining chapters of the dissertation are organized as it follows:

Chapter 2. Describes the complexity of the facial rigging process and discusses different methods related to facial synthesis: shape interpolation, geometric deformation, physically-based, motion capture and retargeting. It briefly describes facial parameterization, Facial Action Coding System (FACS) and the MPEG-4 Facial Animation standard. After that, it details the pipeline of a sketch-based system: sketch acquisition, filtering and interpretation, and then it describes some systems that use sketching to generate facial deformation. Lastly, it discusses several open issues related to the fields of facial animation and sketching interaction.

Chapter 3. Describes *Sketch Express*, the proposed control system to create facial expressions through free-hand sketching. The chapter begins by defining the major problems found and presenting some main challenges to overcome at both levels, the rig control and the sketching interaction model. After that, it gives an overview of the developed facial control system and then it details the sketching control method developed in this research. Lastly, it presents the framework implemented for prototyping purposes.

Chapter 4. Describes two experiments conducted with users: Facial Posing Experiment and Facial Retargeting Experiment. The results obtained from experiments were analyzed after statistical validation. It also summarizes the results of a test to measure the system performance. Lastly, it presents an application of the developed sketching method in the psychotherapy field.

Chapter 5. Discusses the work developed in this research, its implications and future trends.

Chapter 2

Background and Related Work

One of the most important aspects in virtual character animation is facial expression. The central research goal is to create real time facial synthesis with high artistic quality. But, generating correct skin deformation raises several challenges at the level of facial rig control. This chapter begins by defining a facial rig as a structure that needs to be controlled by an user interface. Then comes an extensive study of the published literature and previous work in facial synthesis and parameterization. After that and motivated by the ease of freehand drawing to simplify the user interaction model, we focus our research on the study of the sketch-based interfaces. The chapter ends with a discussion about several open issues related to the research fields of facial animation and sketching interaction. After reading this chapter, you should have an understanding of the underlying work that is related with this research.

2.1 Traditional Animation Pipeline

The film and videogame industries typically use a production environment, which is divided into the following stages: concept design, modeling, rigging and animation (see Figure 2.1). After the concept design of a character is finished, 3D artists need to model, rig and animate the character [Schleifer et al. 2002]. During the modeling stage the geometry of the model is created based on the visual requirements defined during the concept design. After that, a control structure, usually named *rig*, is defined and the model is ready to become animated. Rigging is then an intermediate process that links the modeling and animation stages within a traditional animation pipeline.

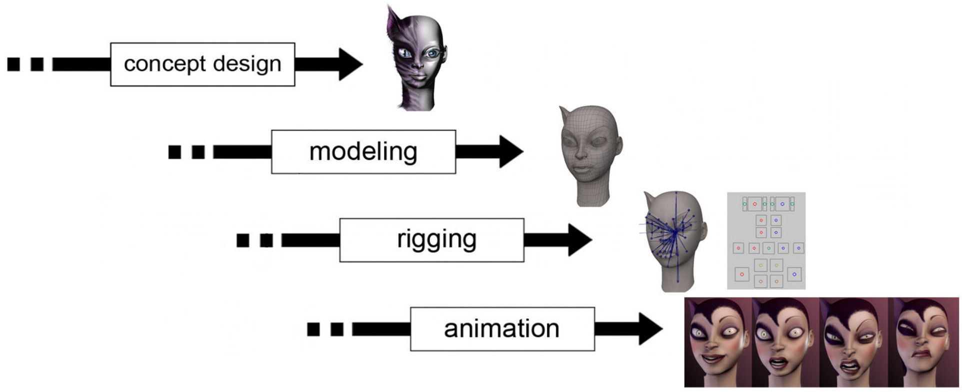


Figure 2.1: Different stages in a traditional animation pipeline. Notice that the modeling, rigging and animation stages work in parallel. The rigging stage produces a rig that will be manipulated in order to animate the 3D model. Sometimes it is necessary to readjust the rig after starting the animation stage, because the rig does not perform the desired movements in the 3D model.

The person responsible for rigging a character, usually known by Rigger, needs to interact with both, the modelers and the animators, in order to realize how to create the rig to improve the model's deformation. It is his responsibility to provide an efficient and intuitive interface that allows the animator to control the character's face [Parke and Waters 2008].

In the case of complex facial models, it is challenging to setup a consistent rig that can work well for every possible motion. It is usual that after the rig is defined, the animator asks the rigger to generate new controls, because the character needs to support new deformations or just needs to look better. Thus, the overall process gets iterative and, therefore, becomes a serious problem in a CG production pipeline [Orvalho et al. 2012].

The following sections define a facial rig as a structure that needs to be controlled. It also describes the different approaches to manipulate a rig.

2.1.1 Facial Rig

One of the most complex tasks in facial animation is the creation of a rig that adapts the face model to the shape and visual style of each character and produces convincing facial expressions. When creating a facial rig it is important to consider the face's *morphology* and *behavior* [Orvalho et al. 2012]. The *morphology* is related to the shape and visual appearance of the 3D face. The *behavior* corresponds to the facial movements the 3D model will do. Given the fact that there is a lack of a formal rig definition, different authors and riggers have adopted a variety of explanations. For example, according to Falk et al. [Falk et al. 2004], *"'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"'*. McLaughlin and Sumida [McLaughlin and Sumida 2007] state that *"'Rigging is the system engineering process that allows surface deformation"'*. Based on these two definitions, we can define a rig as a set of controls that can be manipulated to deform a 3D model, which is a process analogous to setting up the strings that control a puppet.

The most common approaches to create a facial rig are based on *blendshapes* interpolation methods, *bone-drive* methods or a combination of both. A rig based on blendshapes consists on sculpting facial poses into several meshes of the same topology [Maraffi 2003], where each new mesh is called a shape (see Figure 2.2).

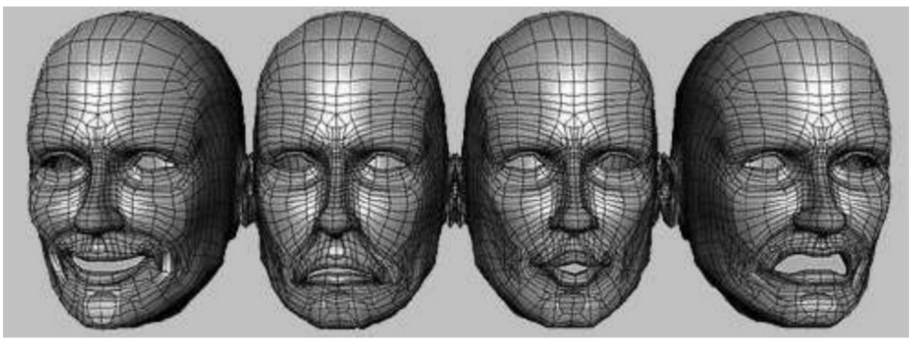


Figure 2.2: Blendshapes that represent the basic expressions: happy, sad, surprise and angry (Copyright 2004 New Riders Publishing).

Interpolating between several shapes generates facial animation. For example, the interpolation between the closed and the open eyes shapes creates the blinking eye animation of the character. So, creating a rig of a facial model using only blendshapes, is a hard task, since the artist needs to sculpt a large number of shapes [1] to provide deformation over every region of the face. The artist controls the weight of the shapes and blend them to generate the animation. This process needs to be repeated for every character that is going to be animated and consumes a long time for production. Several researchers [Orvalho 2007; Dutreve et al. 2008; Dutreve et al. 2010] proposed a method to automatically transfer shapes among different characters, considerably reducing the time of production.

A bone-driven rig is based on a highly articulated facial skeleton structure bind to the 3D surface. To create this binding between the skeleton and the mesh it is necessary to define how the skeleton bones influence each vertex surface. Normally, this is done through smooth skinning algorithms [Yang and Zhang 2006]. As each vertex is only animated by the bones around it, much more planning must go into rigging process of each model [Ward 2004]. Figure 2.3 shows an example prepared to be animated.

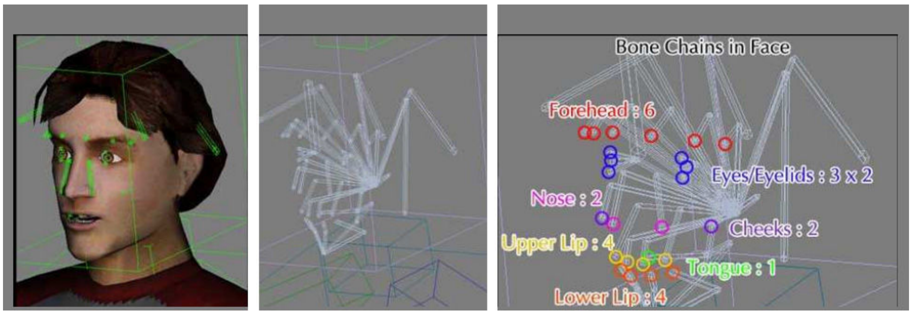


Figure 2.3: A bone-driven rig based on a highly articulated facial skeleton structure. The skeleton is composed of around 34 bones. (Copyright 2001-2007 Epic Games).

The skeletal approach allows the creation of softer movements than the blendshapes method, although it requires a longer time of preparation to get good results [Ward 2004]. In videogames production, bone-based rigs are widely used together with Motion Capture techniques (see section 2.2.4), which each bone of the rig can represent a motion sensor placed on the face.

Two main concerns in computer animation are, naturally, time and produc-

[1]In the film *The Lord of the Rings: The Two Towers*, the rig of the character *Gollum* implied the creation of 675 shapes [Fordham 2003].

tion costs. So, it is essential to guarantee that the rigging technique is the one that best suits the project. Both methods based on blendshapes and "bones" present advantages and disadvantages. A typical choice is to combine blendshapes with a skeletal approach, which provides a rig with the flexibility and smoothness of a bone-driven system, as well as, the expressiveness of blendshapes [Lewis et al. 2000; Lewis and Anjyo 2010].

In face regions where neither shapes nor "bones" produce the desired results, it is possible to add new layers of deformation [Orvalho 2007]. These new objects are commonly denominated as influence objects or deformable objects; they add control and give additional realism to the animation. NURBS curves or FFD grids (see section 2.2.2) are an example of this type of deformation objects, which can be added in some regions of the face in order to emphasize some characteristics, like muscles, wrinkles, etc.

As a summary, a typical rig includes the following elements:

1. **Skeleton**: hierarchical and articulated structure composed by bones and joints. Each bone is connected by two joints. The deformation of the mesh is influenced by the action of the skeleton's joints.

2. **Deformable objects**: any object that can be deformed, like NURBS curves or surfaces, polygonal meshes, lattice objects and others. These objects, connected to the skeleton, add extra control and realism to the animations and can represent the geometry of, for example, facial muscles and simulate its behavior.

3. **Skinning**: the process of binding skeleton's joints to the correspondent vertex of the polygonal mesh and to the deformable objects. There are different skinning techniques, like smooth or rigid skinning [Larboulette et al. 2005; Yang and Zhang 2006], and the most important task during this process is the weight definition [Wang and Phillips 2002]. The weight is the degree of influence of a joint over a vertex during deformation. Each joint and deformable object has its own weight distribution map, which defines the amount of influence they will exert on the model during animation [Mohr and Gleicher 2003].

4. **Shapes**: set of poses or facial expressions. The interpolation of the different shapes results in the facial model animation.

5. **Constraints**: restrictions of position, rotation and scale in order to avoid impossible and unwanted movements.

The rig definition is an iterative process that requires great amount of production time, experience and knowledge about the facial anatomy. An experienced artist can take from one to several weeks to rig a character, depending on the complexity of the rig [Ritchie 2006].

2.1.2 Rig Control Interface

Usually, to deform a 3D face, the artist needs to understand the rig as a structure that has to be manipulated by an user interface (UI). The rig's UI can be defined as a set of controls that allows the user interaction in order to modify the underlying geometry of the 3D model. There are a considerable amount of different approaches to handle the controls of a rig. These approaches to the UI for rigging can be compiled into two categories: *window-based* and *viewport-based*, which can also be combined.

Window-based UI uses a traditional interface design to provide direct input of values. The UI is built in a separate window, not in 3D space. Holly [Holly 2006] has built a UI with sliders that ease the manipulation of controls located in the facial skin surface of a stylized character (see Figure 2.4 left). Villagrasa and Susin [Villagrasa and Susin 2009] have built an UI based on FACS [Ekman and Friesen 1978]. By editing parameters, their system allows to move the muscles of a realistic character to generate different expressions of the face (see Figure 2.4 right).

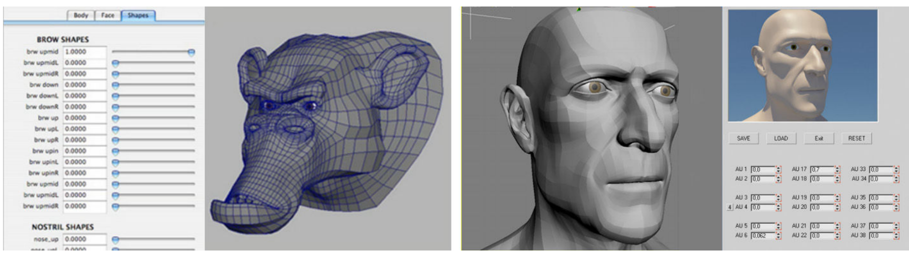


Figure 2.4: Window-based UI; left: slider-based UI to control the activation of blendshapes for the stylized character's eyebrows and nostrils [Holly 2006]; right: slider-based UI based on FACS for a realistic character's face [Villagrasa and Susin 2009]

Viewport-based UI provides a set of controls (2D or 3D) that make part of the 3D space where the model is located. Several authors [Osipa 2007; Neale 2008; Maguire 2008; Skonicki 2008; Alexander et al. 2009; Grubb 2009; Komorowski et al. 2010] have created the UI in 3D space to control the characters' face. Osipa [Osipa 2007] proposed a set of 2D controls constrained to a square to drive the activation of blendshapes. Alexander et al. [Alexander et al. 2009] have used the same technique of a 2D constrained space, but with an anthropomorphic shape control. The blendshapes are controlled by a UI built with arrow-shaped control curves. Each arrow of the UI controls the correspondent region of the 3D face (see Figure 2.5 up left). Skonicky [Skonicki 2008] has changed the position of the facial bones through the 2D controls located in the UI (see Figure 2.5 up right). Grubb [Grubb 2009] and Komorowski et al. [Komorowski et al. 2010] have handle a set of 3D controls to drive the facial deformation in the 3D space (see Figure 2.5 down).

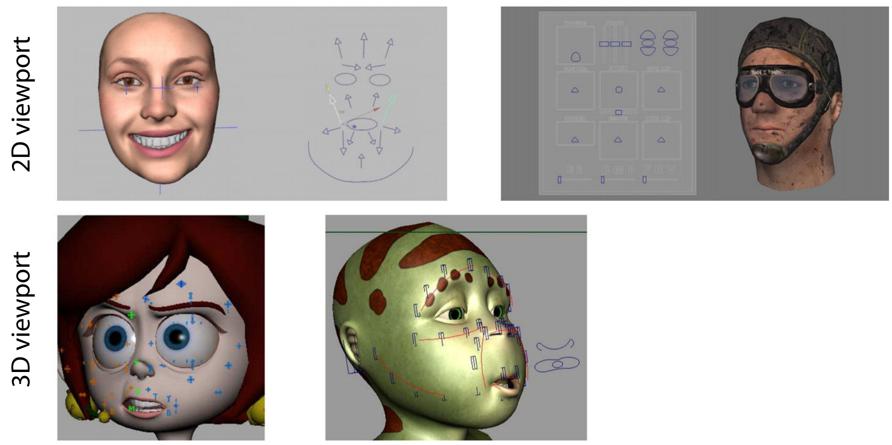


Figure 2.5: UI in 3D space to control the character's face; up: example of 2D controls by Alexander et al. [Alexander et al. 2009] and Skonicky [Skonicky 2008]; down: example of 3D controls by Komorowski et al. [Komorowski et al. 2010] and Grubb [Grubb 2009].

The following section discusses the most relevant methods related to facial animation.

2.2 Facial Animation

Human facial expression has been studied for more than one hundred years. Computerized facial animation began in the 70's. It is interesting to understand that the techniques that are used nowadays come from the principles developed more than forty years ago. The first 3D facial animation was created by Frederic Parke [Parke 1972]. Since then, different approaches have been developed and were classified into two major categories: 3D Geometric manipulation and 2D image manipulation. It is not easy to fit a certain method into one of these categories, since the boundaries between both are not clearly defined. In 1998, Noh and Neumann [Noh and Neumann 1998] and more recently Deng and Noh [Deng and Noh 2007] presented a survey that classifies different facial animation methods. Facial analysis and comprehension is another area that influences recent facial synthesis tendencies. Zhao et al. [Zhao et al. 2003] presented a detailed document about facial recognition that gives a different perspective and complement this research field.

The following sections describe the most common approaches used for facial modeling and animation: Shape interpolation, Geometric deformation, Physically-based, Motion Capture and Retargeting.

2.2.1 Shape Interpolation

Shape interpolation is the most commonly employed technique in facial animation. It consist on specifying complete face models for a given set of points in time, called blendshapes, key poses or morph targets. Each blendshape represents a specific face deformation and the models for the intermediate frames are generated by interpolation. The simplest case to be mentioned corresponds to an interpolation between two keyframes at different positions in time (see Figure 2.6). For blendshape interpolation, all the shapes must have the same structure. That is, they must have the same number of vertices with the same connectivity and each vertex must have a matching vertex in the other blendshapes. A face deformation then becomes a linear combination of a number of blendshapes.

Linear interpolation is frequently used because of its simplicity [Bergeron and Lachapelle 1985; Pighin et al. 1998], but a cosine interpolation function

Figure 2.6: Linear Interpolation using blendshapes; left: Neutral pose; right: "A" mouth shape; middle: Interpolated shape [Deng and Noh 2007].

[Waters and Levergood 1993] or other variations, such as spline, can offer acceleration and deceleration effects at both limits extremities of an animation. Bilinear interpolation creates a greater variety of facial expressions than linear interpolation, when, instead of two, four keyframes are involved [Parke 1974]. When combined with simultaneous image morphing, bilinear interpolation produces a broad range of different facial expressions [Arai et al. 1996].

There were recently some attempts to improve muscle actuation based on blendshape animations [Choe and Ko 2001; Sifakis et al. 2005]. The Pose Space Deformation technique introduced by Lewis et al. [Lewis et al. 2000] offers a framework for example-based interpolation, which can be used in blendshape facial animation. In their work, the deformation of a face is dealt as a function of some set of abstract parameters (such as lip stretcher or nose wrinkler) and scattered data interpolations creates a new facial pose.

Interpolations are quick and can easily create facial animations. Nevertheless, they show limitations when creating a broad variety of realistic facial expressions. Combinations of independent facial poses, like eye closed while smiling, are difficult to produce and blendshapes often interfere with each others [Deng and Noh 2007], which forces animators to go backwards and forwards to readjust the weights of blendshapes. So, further research is required to automate the blendshape approach, which currently requires a lot of manual work to perform a successful animation. Lewis et al. [Lewis et al. 2005] introduced a method to automatically reduce blendshape interferences. Recent advances show that blendshape interpolation is being used in combination with other animation methods, like performance-driven techniques

[Igarashi et al. 2005; Deng et al. 2006; Li and Deng 2008; Liu et al. 2011], to significantly reduce the amount of manual work.

When the facial model complexity increases, the manipulation of a large number of blendshapes becomes a problem. Lewis and Anjyo [Lewis and Anjyo 2010] presented a method for direct manipulation of blendshapes. Their method uses PCA to automatically create a space where each blendshape has a correspondent position in the 3D space. They show that a single direct manipulation in the 3D space is usually equivalent to a large number of edits using the traditional sliders, resulting in a simple and efficient technique, compatible with existing blendshapes approaches. Later, Seo et al. [Seo et al. 2011] extended the previous method to control efficiently and intuitively a large number of blendshapes with a hardware-accelerated optimization. Their approach leads to a huge improvement in both storage and processing efficiency without suffering any visual artifacts.

Recently, Liu et al. [Liu et al. 2011] proposed a method to automatically explore the non-linear relationship of blendshape facial animation from captured facial expressions. The results of their approach show that more realistic facial animation can be synthesized when compared to techniques that use linear functions.

2.2.2 Geometric Deformation

Geometric deformation methods consist on using an object to modify another more complex object, by presenting an easier or simpler control interface. They are efficient for modeling and animating deformable objects, because they provide a high level of geometric control over the deformation.

A typical geometric approach is free-form deformation (FFD). It was first introduced by Sederberg and Parry [Sederberg and Parry 1986] and uses a lattice to control the 3D model deformation. In theory, a flexible object is embedded in an imaginary and flexible control box containing a 3D grid of points (see Figure 2.7). As the control points are manipulated, deforming the control box, the embedded object deforms accordingly.

To provide the artist with more control Chadwick et al. [Chadwick et al. 1989] used FFD for multi-layered construction and animation of deformable

Figure 2.7: FFD applied to a spheric surface; left: neutral position; right: object deformation [Deng and Noh 2007].

characters. Coquillart [Coquillart 1990] extended FFD (EFFD) to support more general lattices but lost some of the flexibility and control, so MacCracken and Joy [MacCracken and Joy 1996] have developed a method that allows the user to define lattices of arbitrary topology. However, the manipulation of individual control points makes FFD and EFFD boring methods to use.

Other geometric deformation methods related to character animation where introduced: Turner and Thalman [Turner and Thalmann 1993] defined an elastic skin model; Singh et al. [Singh et al. 1995] used implicit functions to simulate skin behavior; and Wu et al. [Wu et al. 1996] studied skin wrinkles. Lewis et al. [Lewis et al. 2000], used radial basis functions to develop a pose space deformation technique for facial skin and skeleton-driven animation. Advantages of this algorithm include improved expressive power and direct manipulation of the desired shapes. Joshi et al. [Joshi et al. 2003] proposed an automatic physically segmentation that learns the controls and parameters directly from the set of blendshapes to create facial animation.

Recent approaches are oriented to shape modeling by gestures [Angelidis and Cani 2004; Gain and Marais 2005; Kil et al. 2005]. The user describes a deformation by dragging a point along a path. The method is independent of the geometric shape representation, preserves volume and avoids self-intersections. More recently, Nataneli and Faloutsos [Nataneli and Faloutsos 2007] presented a sketch-based interface for driving facial expressions. Unlike existing solutions [Chang and Jenkins 2006], Nataneli's approach relies on recognition and constructs a semantically relevant representation of a sketched face. These methods provide users with easy controls to generate animations, but automating the related actions still requires significant effort.

2.2.3 Physically-based

Phisically-based methods simulate the elastic properties of facial skin and muscles to generate expressions and animations, as well as, to build facial models. The principal methods used in this approach are mass-spring systems and finite elements algorithms.

Platt and Badler [Platt and Badler 1981] developed the first 3D facial animation using a muscle-based model. He used the mass-spring concept to simulate the forces generated by muscles and used FACS encoding. Waters [Waters 1987] defined three different types of muscles that were connected to the surface and were independent of the bone structure. This aspect made the animation process easier and allowed the muscles transference to faces with different typologies. The facial expressions in this model were obtained through simple geometric distortions controlled by a small number of parameters, but it had the defect on those movements that required subtle details. Magnenat-Thalmann et al. [Magnenat-Thalmann et al. 1988b] introduced a new concept - abstract muscle action (AMA), defined by a set of procedures. An AMA system allows the simulation of a specific facial muscle and is responsible for a specific face parameter. Each facial expression is considered as a group of parameters with values obtained through AMA procedures. Terzopoulos and Waters [Terzopoulos and Waters 1990] developed the previous work of Waters with a new model that includes techniques based on physics and facial anatomy, which allowed much more realistic surface deformations. It is curious to appreciate that, currently, most of the physics-based models still follow the Waters basic principles.

Lee et al. [Lee et al. 1995] created a muscle model composed by multiple layers that, together with a mass-spring system, allowed the deformation of the face surface. This approach presented a great realism and accurate results but with a high computational cost. Basu et al. [Basu et al. 1998] described a model for tracking and reconstruction of 3D human lip motion from a video stream. This physically-based 3D model of the lips was created using finite elements, and the developed model is able to, automatically, make the correspondence between the data from the video and the related parameters on the 3D model. Choe et al. [Choe and Ko 2001; Choe et al. 2001] presented a system to synthesize facial expression based on the data obtained from motion capture (MoCap) but the results continued to present lack of anatomic precision. A promising anatomical model was described by Kahler et al. [Kahler et al. 2001; Kahler et al. 2002] that included different types of muscles and managed some effects, like bulging and intertwining muscles fibres. The skin deformation was performed by the contraction of the muscles, which used a mass-spring system connected to the skull, muscle and skin layers. Sysen et al. [sen Tang et al. 2004] described a NURBS muscle-based system to simulate 3D facial expressions and talking animations. The NURBS curves represented the different muscles that were positioned on the face according to the anatomic knowledge. Muscle deformation was obtained through the manipulation of different control points of the curve and changing the weight distribution.

Sifakis et al. [Sifakis et al. 2005; Sifakis et al. 2006] developed one of the latest and more advanced muscle based models. The system captures the facial movement through markers correctly spread on the face and implements a non-linear finite elements method to accurately determine each muscle action. An interesting feature of this implementation is the fact that external forces (for example, due to an object collision) can interact with the muscles and, consequently, change the final appearance of the face (see Figure 2.8). This method showed the success and importance that motion capture represents in the field of facial animation.

Figure 2.8: Impact of a colliding object on the face [Sifakis et al. 2005].

Ronald Fedkiw's research team has been exploring interesting approaches for modeling highly deformable solids that preserve the volume, based on ideas from computational fluids dynamics [Irving et al. 2007; Shinar et al. 2008].

2.2.4 Motion Capture

Facial motion capture (MoCap) or facial performance-driven technology allows capturing the complex deformations of a human face. The acquired data is then mapped to a 3D model and reproduced to animate virtual characters (see Figure 2.9).

Figure 2.9: MoCap. Each sensor placed on the actor's face represents a marker on the 3D model (Copyright 2007 SoftImage).

The speed-up over animations created "‘by hand"’ as well as the potential for producing more realistic facial motion are some of the advantages of MoCap systems.

Performance-driven methods use both image and geometry manipulation techniques. Early attempts go back to [Waters 1987; Lee et al. 1995], where it was possible to digitize facial geometries through the use of scanning range sensors and animate them through the dynamic simulation of facial tissues and muscles. These advancements led to further research related to motion estimation from video. William [Williams 1990] was the first to synthesize expressions by changing the 2D texture coordinates using the differences between static images. Guenter et al. [Guenter et al. 1998] extended previous work and recovered data from a video stream. Kouadio et al. [Kouadio et al. 1998] used pre-modelled 3D facial expressions and blending techniques to generate real-time animation.

The majority of these methods trace the facial markers from a performer, extract the 2D or 3D positions of these markers, and animate a 3D face mesh. According to [Orvalho 2007], a marker-based motion capture system supports between 30-160 markers on the face, resulting in a very sparse representation of the movements. While this sparse information works well for capturing the motion of rigid objects, it is not very effective for capturing the subtleties of expressive deformable surfaces, like the face. The limitations of marker-based systems have encouraged the development of a variety of markless motion capture systems [Blanz et al. 2003; Schreer et al. 2008; Alexander et al. 2009] and facial feature tracking from video using complex models [Reveret and Essa 2001; Anderson and McOwan 2006; Fasel and Luettin 2003].

Many performance-driven techniques have emerged. Borshukov et al. [Borshukov et al. 2003] use an optical flow and photogrammetric technique to record a live actor's performance. Optical flow refers to a technique of tracking each pixel in time using multiple cameras. The spatial position of each pixel can later be determined using triangulation. Blanz et al. [Blanz et al. 2003] combine image-based and geometry-based technologies to augment the performance by simulating motion that has not been performed. Zhang et al. [Zhang et al. 2003] also combines image-based and geometry-based technologies, but for the purpose of simulating subtle facial details such as wrinkles that cannot be identified through performance.

Motion capture technology is changing dramatically and new methods continue to appear. Zhang et al. [Zhang et al. 2004] designed a system of several video cameras positioned around the performer. No facial markers were used hence the footage is also suitable for texture and lighting purposes. Borshukov et al. [Borshukov et al. 2006] used a more robust capture technique to obtain a high quality facial data and a novel encoding technique, based on Principal Component Analysis (PCA), to encode the facial data. It has been recently shown that performance-driven techniques combined with other animation approaches, like blendshape [Deng et al. 2006; Li and Deng 2008], give users the complete control over the face animation. While Deng et al. [Deng et al. 2006] tuned the weights of the blendshapes through Radial Basis Function (RBF), Li and Deng [Li and Deng 2008] used PCA to change the blendshape's weights.

Actually, nothing is more natural than the actual expression created by real people. If such expressions are accurately captured and reproduced, the results are quit astonishing. Thus, methods based on performance-driven data can generate realistic facial motion but continue to be expensive to use and more appropriate for realistic faces than cartoony look. Furthermore, some other limitations remain unsolved, like how to accurately capture the inside of the lips.

Performance-driven methods will continue to improve using machine learning or interpolation techniques, and will complement current animation and rigging techniques [Pighin and Lewis 2006]. Bickel and his colleagues [Bickel et al. 2007; Bickel et al. 2008] present interesting approaches for real time animation of highly-detailed facial expressions, such as expressions wrinkles.

Recently, Beeler et al. [Beeler et al. 2011] described a new technique for markerless facial performance-driven capture. The method uses state-of-the-art stereo reconstruction to acquire high resolution per-frame geometry. Then, a single triangle mesh is generated and propagated through the entire performance. The results show that the implemented system is able to reproduce extreme deformations as well as expressive and fast facial motions. Huang et al. [Huang et al. 2011] presented a novel acquisition framework for capturing high-fidelity 3D facial animation with realistic dynamic wrinkles and fine-scale facial details. Their approach combines state-of-the-art marker-based motion capture technology to record high-resolution dynamic facial motions with advanced 3D scanning technology to record high-resolution static facial geometry. Weise et al. [Weise et al. 2011] demonstrates that convincing 3D facial dynamics can be reconstructed in real time without the use of facial markers or complex scanning hardware. They presented a novel face tracking algorithm that combines 3D geometry and 2D texture registration with blendshapes generated from pre-recorded face animation sequences.

2.2.5 Retargeting

The concept of retargeting is related to the synthesis of facial motion by reusing existing data. It consists on directly mapping motion from a source to a target model of different proportions, where the source data has to be adapted to the target model shape, making the target animatable.

The name was first introduced by Gleicher [Gleicher 1998], who presented a method for transferring motion capture data between characters, which share the same structure but might have different sizes. The method was well suited for human body structures, but was not prepared to capture the subtleties of facial motion because it lacked facial structure.

Geometric deformations allow the transfer of facial motion between two 3D face meshes. Noh and Newmann [Noh and Neumann 2001] have suggested an "expression cloning" technique, which permits to transfer vertex displacements from a 3D source face model to target 3D face models that may have not only different geometric proportions but also mesh structure. Basically, it is meant to build vertex motion mappings between models through the Radial Basis Function (RBF) morphing. The work by Summer and Papovic [Sumner and Popović 2004] proposes a different solution to the same problem. Where Noh and Newmann estimate local deformations independently at each vertex, Summer and Papovic estimate them using a global optimization. Although based on a sounder mathematical justification, the global approach adopted by this technique has its drawbacks. In particular, the optimization can amplify small mesh imperfections and noise.

A number of approaches were proposed to transfer source facial motions to blendshapes face models, due to the popularized use of blendshape methods in industry practice. Chuang and Bregler [Chuang and Bregler 2002] presented a method that uses a combination of motion capture data and blendshape interpolation. The artist creates the blendshape models, guaranteeing that the shapes will nicely mix during animation, while motion capture data is used to drive the facial movements, rather than hand animation. Sifakis et al. [Sifakis et al. 2005] constructed an anatomically very accurate facial muscle model, using the principles derived from the more general muscle construction principles of [Teran et al. 2005] and then use nonlinear finite element algorithms to determine accurate muscle actions from the motions of sparse facial markers. Deng et al. [Deng et al. 2006] describe a semi-automatic method of cross-mapping of facial data to pre-designed blendshape models. They also improve on the blendshape weight-solving algorithm.

Despite reproducing accurately the facial motions between 3D models, the above mentioned approaches provide little transformation function, for example, change affective mode during transferring. In order to transform facial motions, bilinear and multilinear models were proposed. Bilinear models were used by Chuang and Bregler [Chuang and Bregler 2005] to learn a facial expression mapping function from training video footage. This learned mapping is then applied to transform input video of neutral talking to expressive talking. Vlasic et al. [Vlasic et al. 2005] suggested learning statistical multilinear models from scanned 3D face meshes so as to transfer facial motion in video to other 2D or 3D faces.

2.3 Facial Parameterization

The parameterization process consists on defining an optimal set of parameters that can be used to control facial movements. The objective is to describe the face with a small set of control parameters instead of describing the complete face geometry. Some of the limitations of simple interpolations can be overcome by parameterization techniques. Unlike interpolation techniques, parameterizations allow explicit control of specific facial configurations. Combinations of parameters offer a great variety of facial expressions at low computational costs.

Developing an optimal parameterization is a difficult and complex task. Research has shown that an ideal parameterization does not exist because it is difficult to satisfy all user demands for a broad range of facial applications. Parke developed the first facial parametric model that allowed direct creation of facial deformation by defining ad hoc parameters or by deriving parameters from the structure and anatomy of the face [Parke 1974].

The following sections present two standards that have been used to categorize facial expressions.

2.3.1 FACS - Facial Action Coding System

Eckman and Friesen [Ekman and Friesen 1978] defined the Facial Action Coding Systems (FACS) to describe and measure facial behaviors. FACS, which are frenquently used by both psychologists and animators, have become a standard to categorize the physical expressions of emotions. This standard parameterizes facial expressions in terms of Action Units (AU). AUs, which are based on anatomical muscle and bone movements, stand for the various minimal facial changes, like raising left eyebrow. There are 46 AUs that represent contractions or relaxation of one or more muscles. Along with the definition of various AUs, FACS also provides the rules for AU detection in a face. Using these rules, it is possible to encode a facial expression that produce the expression. For example, combining the AU1 (Inner Brow Raiser), AU6 (Check Raiser), AU12 (Lip Corner Puller), and AU14 (Dimpler) creates a happy expression. A set of action units and the basic expressions created by the AUs are presented in Figure 2.10.

AU	FACS Name	AU	FACS Name	AU	FACS Name
1	Inner Brow Raiser	12	Lid Corner Puller	2	Outer Brow Raiser
14	Dimpler	4	Brow Lower	15	Lip Corner Depressor
5	Upper Lid Raiser	16	Lower Lip Depressor	6	Check Raiser
17	Chin Raiser	9	Nose Wrinkler	20	Lip Stretcher
23	Lip Tightener	10	Upper Lid Raiser	26	Jaw Drop

Basic Expressions	Involved Action Units
Surprise	AU1, 2, 5, 15, 16, 20, 26
Fear	AU1, 2, 4, 5, 15, 20, 26
Anger	AU2, 4, 7, 9, 10, 20, 26
Happiness	AU1, 6, 12, 14
Sadness	AU1, 4, 15, 23

Figure 2.10: FACS; upper row: Sample single facial AUs; lower row: Sets of AUs for basic expressions [Deng and Noh 2007].

FACS is broadly used with muscle-based approaches, because of its simplicity [Deng and Noh 2007]. Muscle based parameterization became a popular method to define face deformation, because it uses the anatomical knowledge of the face to define the behavior of human skin, bone and muscle system. In this approach, the parameters control the face through functions, which emulate or simulate muscle actions [Waters 1987; Magnenat-Thalmann et al. 1988b]. Generally, this method is hard to animate, because the face has many bones and muscles that need to be controlled to obtain a realistic movement. So, it needs a higher-level layer linked to the muscles, which simplifies the animation control interface.

Although FACS are very popular, there are some drawbacks when using them [Ekman 1993; Pelachaud et al. 1994; Essa et al. 1996], since AUs are just local patterns while actual facial motion is seldom completely localized. Moreover, FACS do not offer temporal components, just spatial motion descriptions. In the temporal domain, co-articulations effects are lost in the FACS system. Several researchers have claimed that the timing of expressions, something that is completely missing from FACS, is a critical parameter in recognizing emotions. Another problem in using an anatomically correct system, like FACs, is its rigidity, that makes difficult to obtain facial models with artistic quality.

Another kind of parameterization is based on feature points, that are sparse on the face to accurately make facial deformations. This approach uses the empirical study of the face to determine the set of parameters. The first work was by Parke, who in addition to empirical studies of human faces, used traditional hand drawing to select the parameters [Parke 1974]. Later, Guenter et al. [Guenter et al. 1998; Guenter et al. 2005] presented a method, in which a large set of feature points was linked to the closest control point of the face geometry, so changing the feature point position caused a deformation on the face model.

2.3.2 MPEG-4 Facial Animation

The MPEG-4 Facial Animation standard [Pandzic and Forchheimer 2002] specifies and animates 3D face models by defining a set of Feature Points (FP). The main purpose of the FPs is to provide spatial reference to specific positions on a human face such as major muscles and bones (see Figure 2.11 left). The standard also specifies Facial Animation Parameters (FAPs), which move the FPs producing the animation. The specification defines 66 low-level FAPs and 2 high-level FAPS. The low-level FAPs are based on the study of minimal facial actions and are closely related to muscle actions. They represent a complete set of basic facial actions, and therefore allow the representation of most natural facial expressions. Exaggerated values permit the definition of actions that are normally not possible for humans, but could be desirable for cartoon-like characters. All low-level FAPs are expressed in terms of the Face Animation Parameter Units (FAPUs), illustrated in Figure 2.11 right.

These units are defined in order to allow interpretation of the FAPs on any face model in a consistent way, producing reasonable results in terms of expression and speech pronunciation. They correspond to distances between key facial features and are defined in terms of distances between the FPs. For each FAP, it is defined on which FP it acts, in which direction it moves, and which FAPU is used as the unit for its movement.

The specification still includes two high level FAPs: expression and viseme. An expression represents the facial emotion of the character and the specification defines the 6 basic facial expressions: Joy, Sadness, Anger, Fear, Dis-

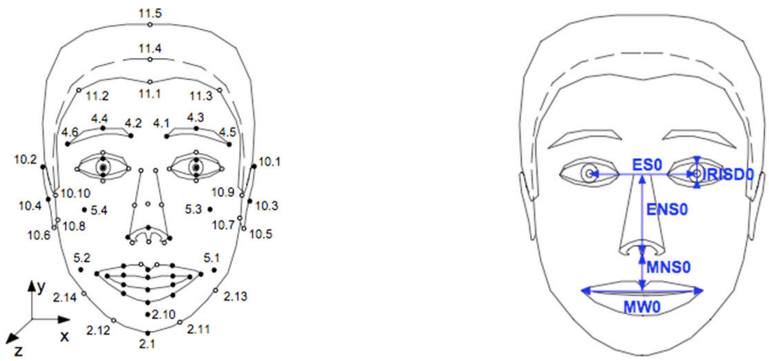


Figure 2.11: MPEG-4 Facial Animation; left: Facial Feature Points. The specification defines 84 FPs for a face; right: Face Animation Parameter Units (FAPU) [Balci 2004].

gust and Surprise. Viseme is a phoneme visual representation and specific the mouth position for its particular articulation. The viseme parameter can contain a predefined list of 14 visemes.

Previous research efforts on MPEG-4 facial animation were focused on deforming 3D face models based on MPEG-4 feature points [Escher et al. 1998; Kshirsagar et al. 2001] and building MPEG-4 facial animation decoder systems [Abrantes and Pereira 1999; Lavagetto and Pockaj 1999; Garchery and Thalmann 2001; Pandzic 2002]. For example, Escher et al. [Escher et al. 1998] proposed a free-form deformation technique to deform a generic face model, generating MPEG-4 facial animations. Kshirsagar [Kshirsagar et al. 2001] introduced an efficient feature point based deformation technique given MPEG-4 feature point inputs. Various MPEG-4 facial animation decoder systems [Abrantes and Pereira 1999; Lavagetto and Pockaj 1999] and frameworks that are targeted for web and mobile applications [Garchery and Thalmann 2001; Pandzic 2002] are also proposed.

The range of applications that used some kind of parameterization is constantly growing and novel techniques continue to emerge. Xface is a set of open source tools for creating and editing MPEG-4 and keyframe based 3D talking heads [Balci 2004]. Visage Technologies [2] offers innovative technology for applications involving computer generated virtual characters, based on the MPEG-4 Face and Body Animation.

[2]http://www.visagetechnologies.com

The following section presents some important concepts related to sketch-based interaction.

2.4 Sketching Interaction

The interaction model of traditional modeling systems, such as Maya [3] or Blender [4], uses the traditional WIMP paradigm (Window, Icon, Menu, Pointer). These applications are powerful and accurate, but they have cumbersome interfaces which increase the learning time and make them difficult to use. The user needs to make many clicks to perform a specific operation or needs to memorize keyboard shortcuts. These tools are certainly suitable for professional artists, but they are not accessible for beginners or non-expert artists.

The use of gestures or strokes has been a recent research direction in modeling interfaces in order to simplify the user interface [Olsen et al. 2009]. Instead of requiring the user to work with traditional buttons, menus, and dragging operations, freehand drawing allows them to directly express their ideas in a natural way. This trend, known as sketch-based interfaces and modeling (SBIM), is motivated by the ease of sketching and the human ability to instill so much meaning into a 2D drawing. Sketch-based interfaces can make 3D modeling systems accessible to novice users.

Research on sketch-based interfaces dates back to the SketchPad System [Sutherland 1964], which allowed the creation and manipulation of objects on a screen, using a light-pen input. However, creating a consistent system that provides a natural interface that understands the user's intention and displays the correct result, is still an open issue. The challenge of sketching is to interpret what the stroke means. Most previous sketching approaches deal with the creation, editing and deformation of 3D models [Zeleznik et al. 1996; Igarashi et al. 1999; Igarashi and Hughes 2003; Mao et al. 2009]. For a more thorough review on sketching, we refer the reader to [Olsen et al. 2009; Cook and Agah 2009].

Based on Olsen et al. [Olsen et al. 2009], the pipeline of a sketch-based system is summarized in Figure 2.12. The first step is to obtain a sketch

[3] http://usa.autodesk.com/maya/
[4] http://www.blender.org/

from the user (Sketch Acquisition), followed by a filtering step to clean and transform the sketch into other representations (Sketch Filtering). The final step of the pipeline is to interpret the sketch as an operation on the 3D model (Sketch Interpretation).

Figure 2.12: The sketching pipeline.

The following sections detail each stage of the sketching pipeline.

2.4.1 Sketch Acquisition

The most basic operation shared between all sketch-based systems is acquiring a sketch from the user. The input to the *Sketch Acquisition* module consists of a freehand drawing generated by the sketch-based input device. It is important that the input device provides the user with a natural interaction. The most common device is the standard mouse, which allows a freehand input. However it does not imitate the real feeling of drawing in a paper. For this reason, devices such as tablet displays are better, since they provide a natural way to draw.

Any sketch-based input device provides spatial information in a 2D coordinate system. The sampling rate varies among devices but in all of them the sampled positions represent a linear approximation of continuous movements (see Figure2.13).

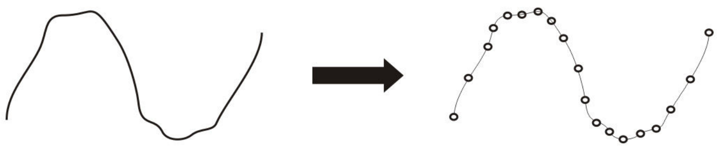


Figure 2.13: The input sketch (left) is acquired as a sequence of point samples spaced irregularly (right).

As the user does not naturally draw with the same speed, the samples become irregularly spaced. In those parts in which the user draws more carefully, like in the corners or curves, the space between samples is smaller, if compared with the samples in a straight line, which are usually farther from one another. Thus, based on [Sezgin et al. 2006; Sezgin 2001], this fact can be exploited to identify the most significant parts of the sketch.

Figure 2.14 illustrates the Teddy bear sketch from Igarashi et al. [Igarashi et al. 1999]. A sketch is made up of strokes. A stroke S can be defined as a time-ordered set of sampled points $S = (p_1, p_2, ..., p_n)$. Each point p_i contains a 2D coordinate and a time stamp: $p_i = (x_i, y_i, t_i)$. The beginning and the end of a stroke is defined by a mouse or pen down and a mouse or pen up events respectively.

Figure 2.14: The Teddy sketch [Igarashi et al. 1999] is composed of several strokes. The artist is creating the left arm with a new stroke.

Strokes can be drawn directly on the 3D model or on a *virtual canvas* (see Figure 2.15). A canvas can be defined as a 2D drawing area specified in a particular plane, such as the XY plane or a user-specified plane, where the sketch can be projected on. The final step is to map the sketch onto the 3D model and interpret it.

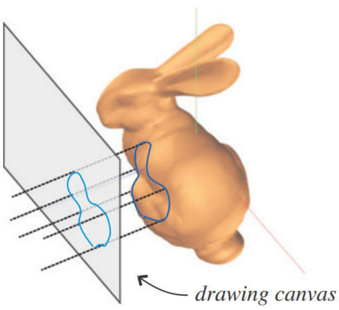


Figure 2.15: The strokes are projected directly on the 3D model or on a 2D virtual canvas by ray casting techniques [Olsen et al. 2009].

2.4.2 Sketch Filtering

After the process of sketch acquisition and before attempting to interpret a sketch, it is necessary to perform some filtering. The filtering process consists of reorganizing the sampled points of the stroke acquired by removing "erroneous samples" or noise. Sezgin and Davis [Sezgin and Davis 2004] divide the problem of noise, identifying two sources of error: *user* and *device error*. *User errors* can occur when the user does not have much skill to draw or to handle the input device, producing an inaccurate stroke. *Device errors* come from an inaccurate capture of the user drawing. It is the "digitization noise" caused by spatial and temporal quantization of the input hardware and vary from device to device.

The spacing between samples in a natural input stroke varies from device to device as well as with the drawing speed of the user. One way to reduce the noise in an input stroke is to *resample* the data. During resampling, it is possible to space the points regularly by discarding some closer points or by interpolating between distant points (see Figure 2.16 left). This can be done on the fly, or after the stroke is finished. Depending on the application needs, linear or smooth interpolation can be used.

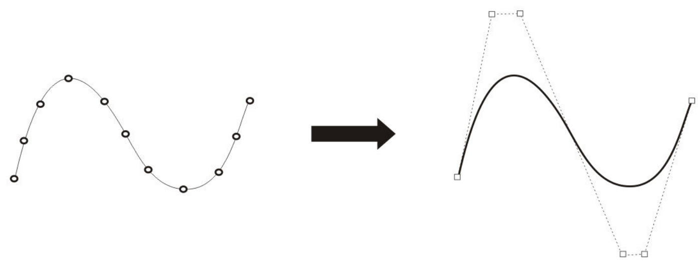


Figure 2.16: Filtering Operations; left: smooth uniform resampling; right: fit to a spline curve.

After resampling data, the result still contains sample points with little meaning. Therefore, it is common to fit them with an equivalent representation, which can be generated by a smaller set of points. *Fitting* the sketch to other representation has advantages such as simplifying the input data as well as the work of future operations and interpretations. Additionally, many of these representations are smooth. Curve fitting is a simplification approach that approximates the data by curves with sufficiently low average error. Least-squares polynomial fitting [Koenig 1998] is an option, and, other approaches use implicit curves and variational subdivision [Alexe et al. 2004; Cherlin et al. 2005; Schmidt et al. 2005]. However the most common approach is the use of parametric curves, like Bézier curves [Piegl 1987; Eggli et al. 1997] and B-Splines [Rogers 1989; Kara and Shimada 2006]. Figure 2.16 right shows one example of spline curve fitting. Most graphics systems use splines to fit curves, because they present good structures and geometric features. Besides the parametric representation, editing the curve is another advantage; actually, it is more intuitive to directly manipulate a point on a spline, than manipulating a certain number of control points [Fowler and Bartels 1993].

In free-form applications where the system needs to make few assumptions about the user's intention, resampling data to have an uniform spatial distribution of the points may destroy some important features of the sketch. We need to give the option to the user draw exactly what they want. Therefore, one problem that arises in this *fitting* level is to know which points of the stroke to choose to parameterize the curve whithout destroying the shape of the stroke drawn by the user.

2.4.3 Sketch Interpretation

After the filtering step, the final stage of the pipeline is to interpret the sketch, which consists on assigning a meaning to it. In other words, the system should interpret the sketch to decide which operation should be performed on the 3D model. In traditional systems (WIMP) this decision is straightforward. Every button, menu or command performs a specific and objective operation. However, in sketch-based systems a freehand input is inherently ambiguous and can have multiple interpretations. This ambiguity obscures the creation of a natural system.

There are many different approaches to lead with this ambiguity. Several authors [Olsen et al. 2009; Cook and Agah 2009; Cruz and Velho 2010] propose a classification of sketch-based systems based on the types of modeling operations. The main categories include operations to *create* 3D models from input sketches and operations to *edit* existing models.

Create 3D models: Olsen et al. [Olsen et al. 2009] divide the methods into two categories: *evocative* and *constructive*. Evocative systems start with a sketch recognition step from a set of predefined templates, and then use the *best candidate* to reconstruct the geometry. Constructive systems do not use the recognition step and reconstruct the geometry from a sketch based only on rules.

There are two types of *evocative systems*: the iconic systems and the retrieval systems. The first approach associates the evocative stroke to a geometric primitive [Zeleznik et al. 1996; Pereira et al. 2000; Contero et al. 2003]. A classic example is the SKETCH system of Zeleznik et al. [Zeleznik et al. 1996], which extrapolates primitive 3D objects from a few strokes (see Figure 2.17 left). The second approach is to retrieve template objects from a database of predefined objects [Funkhouser et al. 2003; Fonseca et al. 2004; Yang et al. 2005; Shin and Igarashi 2007; Lee et al. 2011; Eitz et al. 2012b]. It associates the stroke to a more complete and complex object, instead of simple geometric primitive. A classical example of retrieval system is the Magic Canvas [Shin and Igarashi 2007], that allows to easily build a 3D scene from evocative strokes (see Figure 2.17 right).

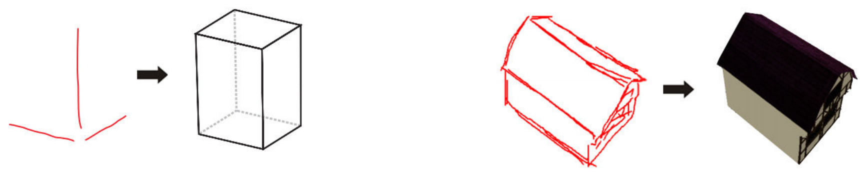


Figure 2.17: Evocative Systems; left: SKETCH is a classical example of an Iconic System [Zelezenik et al. 1996]; right: Magic Canvas is an example of a Template Retrieval System [Shin and Igarashi 2007].

Retrieval results are purely based on geometric similarity between the input sketch and the predefined object. This can help make retrieval systems efficient as it often can be cast as a *nearest-neighbor* problem [Samet 2005]. However, the results can be difficult as users generally draw strokes in an abstract way that is geometrically far from the predefined objects [Eitz et al. 2012a]. Therefore, retrieval systems have to rely on huge amounts of data to offset the problem of geometric dissimilarity between sketches and predefined objects or require users to augment the sketches with text labels [Chen et al. 2009]. Using template matching to identify face parts, Dixon et al. [Dixon et al. 2010] propose a system that helps users to get correct proportions when sketching portraits. Lee et al. [Lee et al. 2011] build upon this idea and developed *ShadowDraw*, a system that dynamically updates a shadow image underlying the user's strokes. The shadows are suggestive of object contours that guide the user as they continue drawing. Their approach uses fast nearest-neighbor matching to find geometrically similar objects and blends those object contours into rough shadow guidelines. As with other sketch-based retrieval systems, users must draw strokes faithfully for the retrieval to work in the presence of many predefined objects. Consequently, users without drawing skills can see no benefit from the system. Recently, Eitz and al. [Eitz et al. 2012b] develop a system for 3D object retrieval based on 2D image techniques (see Figure 2.18). First, they generate a set of 2D drawings for all 3D models existing in a predefined database. Then, they perform matching between the input sketch and those 2D drawings, instead of trying to directly match with the 3D objects. Their approach is based on a *bag-of-features* (BoF) model [Squire et al. 2000; Sivic and Zisserman 2003], which has become the method of choice for affine invariant image retrieval. The basic idea of this approach is to compare images based on a histogram of features.

Figure 2.18: An example of a 3D scene with objects retrieved from a database, built in about two minutes [Eitz et al. 2012].

Construtive Systems consist of interpreting the sketch to reconstruct a 3D model. It has been observed that our visual system chooses to interpret drawings as an object contour [Hoffman 2000]. Therefore, the majority of constructive sketch-based systems adopt to interpret strokes as contour lines [Eggli et al. 1997; Igarashi et al. 1999; Alexe et al. 2004; Tai et al. 2004; Schmidt et al. 2005; Cherlin et al. 2005; Karpenko and Hughes 2006; Nealen et al. 2007]. The contour is defined as the set of the points whose *normal* are perpendicular to the view direction, dividing visible parts of the object from the invisible. Figure 2.19 left shows an example of the contour of an object.

Figure 2.19: left: The contour of an object transmit a lot of shape information; right: the skeleton is used to create smooths 3D objects [Olsen et al. 2009].

Teddy [Igarashi et al. 1999] and ShapeShop [Schmidt et al. 2005] are classical examples of constructive systems based on contours. These systems first calculate the skeleton, which is defined as the set of lines from which the closest contour points are equidistant (see Figure 2.19 right), providing a distance field that aids to define a 3D surface unambiguously (such that the distance from surface to skeleton is related to the distance of contour points to the skeleton). Based on this element, there are different approaches to reconstruct the object's surface. One is to rotate the points of the stroke around the skeleton (see Figure 2.20 left). Another approach is the inflation technique, like the one presented in Teddy (see Figure 2.20 right). Matthew Cook and Agah [Cook and Agah 2009] present a detailed survey on sketch-based 3-D modeling techniques.

Figure 2.20: Construtive Systems; Free form models created from contour sketches; left: example of rotational blending surfaces [Cherlin et al. 2005]; right: example of the inflation technique used in Teddy [Igarashi et al. 1999].

To sum up, despite limited, evocative systems can produce more accurate models from the template set than constructive systems, which can only create basic prototypes or cartoony-looking models. As Karpenko and Hughes [Karpenko and Hughes 2006] states, a mixture of these two systems ”in which the user’s sketch is both inflated and matched against a large database of known forms” would be very effective.

Edit 3D models: Creating a 3D model from sketches is a difficult task and many times conducts to a simplistic reconstruction, so to refine the geometry of an existent model it is necessary to edit it after it is created. The editing process can contain operations such as *Augmentation* [Igarashi et al. 1999; Nealen et al. 2007; Olsen et al. 2005; Biermann et al. 2001], *Cutting* [Nealen et al. 2007; Wyvill et al. 2005; Ji et al. 2006], *Bending* [Igarashi et al. 1999; Kara and Shimada 2006; Cherlin et al. 2005; Wang and Markosian 2007; Ji et al. 2006], *Twisting* [Kho and Garland 2005], *Tunneling* [Schmidt et al. 2005; Nealen et al. 2007], *Oversketching* [Cherlin et al. 2005; Nealen et al. 2005; Zimmermann et al. 2007], *Segmentation* [Ji et al. 2006; Yuan et al. 2005], *Free-form Deformation* [Drapper and Egbert 2003] and *Affine Transformations* [Severn et al. 2006]. Some of these techniques are following described.

Editing an existent model by the use of strokes typically has a straightforward and intuitive interpretation, because the 3D model serves as a reference for mapping the strokes into its own (see Figure 2.15). A stroke is projected onto the 3D model by ray casting techniques. After a stroke has been projected onto a 3D surface, complex details can be produced by displacing the surface along the drawn stroke . Creating elaborated details on an existing model is commonly known by *Augmentation*. Usually the surface is displaced along the *normal* direction, which is appropriate for creating details like veins (see Figure 2.21 left). Another common operation is adding new "pieces" to the 3D model previously created (see Figure 2.21 right). Normally, it uses constructive strokes to define the new piece along with additional strokes that indicate the position where to connect the new piece to the original model [Igarashi et al. 1999; Nealen et al. 2007].

Other sketch-based editing operations use the concept of *Oversketching*. For example, *Bending* and *Twisting* deform an object by making a correspondence between a *reference stroke* and a *target stroke* (see Figure 2.22 left). The reference stroke is used to define the region that will be deformed and the target stroke determines the new shape of the model. Contour oversketching

Figure 2.21: "'Augmenting"' detail on object's surface. left: An example that allows to sketch extra features on the surface of the existing model [Olsen et al. 2005]; right: An example of additive augmentation, which connects a new piece with an existing model [Igarashi et al. 1999].

is also based on matching strokes but, in this case, the reference is a contour automatically extracted from the model (see Figure 2.22 right).

Figure 2.22: Oversketching. left: bending a model so that a reference stroke (red) is aligned with a target stroke (blue) [Igarashi et al. 1999]; right: contour oversketching matches object's contour (yellow) to target strokes (green) [Nealen et al. 2005].

Sketch-based interfaces have also been explored for character animation, using free-form sketches to specify key poses or positions in an animation sequence [Davis et al. 2003; Thorne et al. 2004; Chen et al. 2005]. Davis et al. [Davis et al. 2003] takes a set of figure drawings as input and generates a character animation (see Figure 2.23). By the use of image processing techniques, their system first extracts the positions of the figure joints. After that, it applies geometrical and physical constraints to exclude improbable poses. Finally, the 3D character model is deformed to match the sketched pose.

Instead of drawing each pose, Thorne et al. [Thorne et al. 2004] allow the user to sketch the motion of a character (see Figure 2.24). The shape and timing of the sketching is used to control the motion. The sketch is mapped

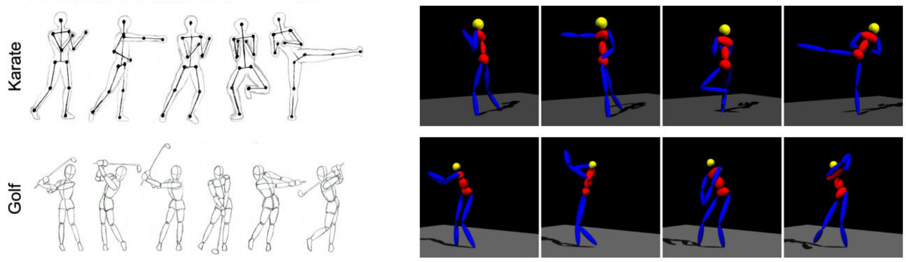


Figure 2.23: Drawn keyframes are shown together with a representation of the final 3D animation [Davis et al. 2003].

to a set of motions predefined in a gesture vocabulary, such as walking and jumping. The system supports a repertoire of 18 different types of motions and combines them accordingly to the sketch. The motion is synthesized employing a parameterized keyframe-based motion synthesis technique.

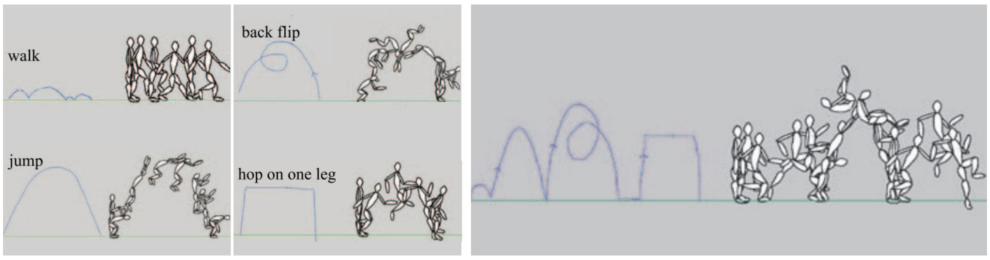


Figure 2.24: Motion Doodles. left: Gesture vocabulary; right: 2D motion sketch and the resulting animation [Thorne et al. 2004].

The following section discusses some systems that use sketching to generate facial deformation.

2.5 Facial Sketching

Using sketching to generate 3D facial expressions has already been explored by other researchers [Chang and Jenkins 2006; Lau et al. 2009; Sucontphunt et al. 2008; Gunnarsson and Maddock 2010]. Facial sketching requires methods that can cope with subtle skin deformation. In contrast to sketching techniques used in 3D objects, the uniqueness and the highly deformable mesh of each face makes facial sketching so challenging. The smallest anomaly in the face shape, proportion, skin texture or movement is immediately detected and classified as incorrect.

Chang and Jenkins [Chang and Jenkins 2006] present a sketch-based interface to drive 3D facial expressions. In their work, users can intuitively draw 2D strokes that are used to search for the optimal facial pose, using a downhill simplex method [Press et al. 1992]. It is possible to change the shape of a face by editing two curves: reference and target. The reference curve allows the user to specify the facial region that will be deformed; the target is used to determine the desired manipulation of the reference curve (see Figure 2.25). This approach does not guarantee realistic facial expressions but is able to create new poses without any prior knowledge.

Figure 2.25: A reference curve (green) and target curve (blue) are drawn on the face mesh to deform the lower lip [Chang and Jenkins 2006]

Lau et al. [Lau et al. 2007; Lau et al. 2009] builds upon this concept but allows animators to use pre-recorded data to eliminate the unnatural expressions that can be generated due to ambiguous user input (see Figure 2.26). The pre-recorded facial models are treated as model priors used to find the posterior model which is the best candidate given the input strokes, based on a mixture of factor analyzers [Ghahramani and Hinton 1997].

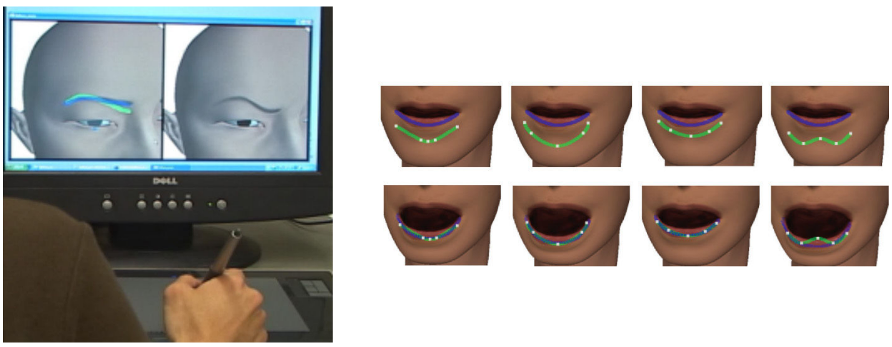


Figure 2.26: Face Poser System; left: an artist using the system; right: the reference curve (blue) defines the moutht's region that will be deformed and the target curve (green) determines the new shape of the mouth [Lau et al. 2009]. The top row shows the inputs and the bottom row shows the results.

In contrast, the method developed by Gunnarsson and Maddock [Gunnarsson and Maddock 2010] relies on predefined reference curves in the form of feature points (FPs), and asks the user only to sketch the target curves. Their method uses prior knowledge in the form of a statistical model that through a maximum likelihood approach [Tipping and Bishop 1998] analyses the sketched strokes, maps the stroke points to the most probable FPs by Hidden Markov Models (HMM) and generates the final pose. This approach is limited to be applied only in regions of the model that have predefined FPs.

Sucontphunt et al. [Sucontphunt et al. 2008] allow creating facial expressions on a 3D model by manipulating the control points of a set of predefined curves on a 2D portrait (see Figure 2.27). A prior knowledge gathered from motion dataset is used in a hierarchical Principal Components Analysis (PCA) model [Jolliffe 1986]. This approach guarantee realistic facial expressions within the scope of the prior dataset but the interaction is limited to the front view.

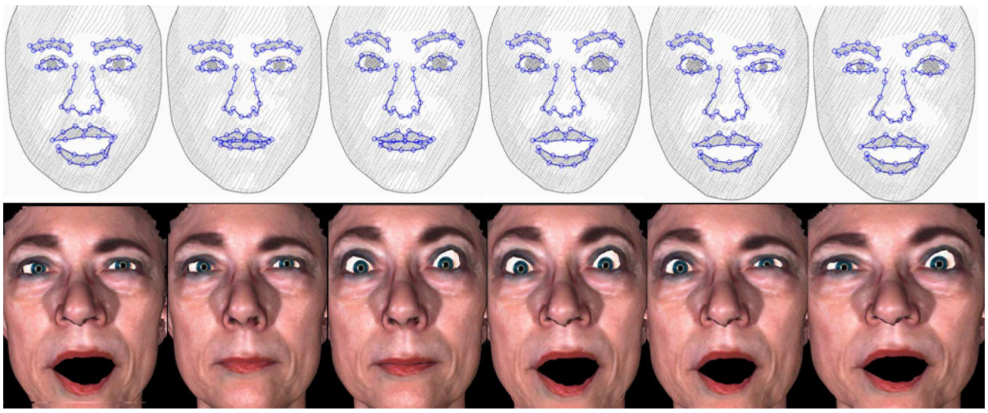


Figure 2.27: The 3D face (bottom row) is automatically deformed based on the 2D portrait (top row) that is being interactively manipulated by the user [Sucontphunt et al. 2008].

2.6 Discussion and Open Issues

In this chapter we presented the most relevant work which has been done by authors in the areas of facial animation and sketching interaction. There are still several open issues related to these research fields that may require further development. What follows intends to deal with some of these issues.

The state-of-the-art techniques to manipulate the rig's controls do not always follow the design of natural interfaces [Norman 2002], making their usability cumbersome for less experienced users. These traditional techniques usually require the manipulation of the rig in a discontinuous way. By discontinuous we mean that the rig's controls are manipulated individually, one by one. So the rig's controls are not encapsulated to generate a complex deformation with just a single and continuous action. For example, the mouth shape presented in Figure 3.8 left requires the user to manipulate, individually, several controls of the UI (see Figure 3.8 middle and right). *Therefore, we feel the lack of an intuitive and efficient interaction model that allows the manipulation of several elements of the rig, at the same time, with just a single control of the UI and through a continuous action.*

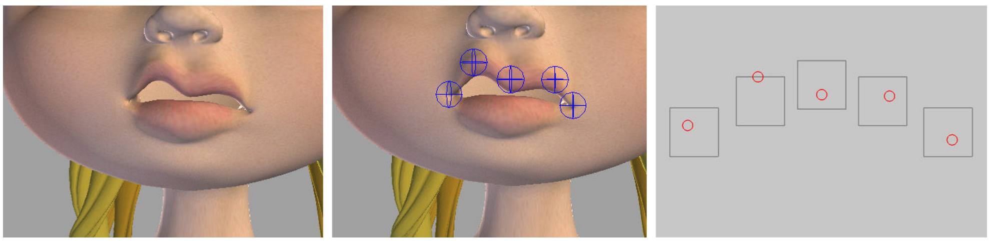


Figure 2.28: Close-up of the mouth region; left: mouth deformation; middle: direct rig control; right: Osipa's rig control; In traditional techniques the user manipulates directly the individual controls of the rig. Notice that it needs to manipulate 5 controls individually to achieve the correspondent mouth deformation;

Many times, the deformations obtained in facial expression during the animation stage are not the desired ones, which make the redefinition of the rig extremely necessary. Thus, both the rig elements and the user interface control system need to be updated to support the new demands. Redesigning the UI whenever a modification in the rig is done makes the process of animation complex and really slow. *Is it not possible to use the same UI to control the* *rig, no matter what alterations are made to the initial rig?*

Our research gives special attention to the creation of a sketch-based interaction model to intuitively deform 3D faces. But, the uniqueness and the highly deformable mesh of each face makes facial sketching absolutely challenging. Any inconsistency in the facial expression is easily identifiable by the spectator, which is an expert at watching faces.

The state-of-the-art methods, based on 2D sketching, provide the users with easy controls to generate 3D facial expressions. These methods usually allow the user to sketch directly on the mesh. However, it is not easy to control directly the details of a surface through a stroke drawn on the mesh and one of the disadvantages pointed to most of the sketching systems is their lack of accuracy [Olsen et al. 2009]. On the other hand, it is known that the deformation of a facial model is usually achieved by manipulating the rig and not by the direct manipulation of the mesh. *Would not it be better to use sketching to control all the elements of the rig instead of controlling directly the vertices of the mesh?*

Most facial sketching systems ask the user to sketch 2 curves: the reference one that indicates the facial region that will be deformed and the target one that indicates the shape of the deformation. It would be more natural and intuitive to deform a certain region of the face with just one curve instead of two curves. *Would not it be possible to indicate both the region of the face to be deformed and the shape of its deformation with just one curve?*

Other systems allow to deform a face by manipulating specific points of a set of predefined curves. These systems do not take advantage of the sketching paradigm since they, actually, do not allow the user to draw strokes but just edit curve points individually. Therefore, the discontinuity problem pointed out to the traditional rig control interfaces remains the same.

To sum up, the main research goal of this thesis is to create complex deformations on any kind of 3D face through an *easy*, *fast* and *intuitive* interaction model, and still generate high quality results.

Chapter 3

Sketch Express: A Control System for Facial Animation

To create deformations in a 3D facial model, artists usually handle the controls of its underlying rig structure. Most traditional approaches allow to manipulate the controls of the rig individually, in a discontinuous way, which is tedious and takes a lot of time. We propose a paradigm shift in the way the rig's controls are manipulated. Instead of handling the controls one by one, with our approach the artist can create complex deformations by drawing free-form strokes. Therefore, it is possible to manipulate several controls of the rig at the same time using just a single and continuous hand movement. We developed a facial sketching control system *that allows the artist to draw strokes directly on the 3D mesh or on a virtual canvas. The system is composed by four modules: Setup, Facial Posing, Pose Retargeting and Facial Animation. These modules are integrated into Autodesk Maya, chosen for prototyping purposes.*

3.1 Problem Statement

Facial Animation is the key element to convey emotions in virtual characters. One of the major challenges in interactive systems (e.g. games, virtual worlds) and off-line systems (mainly used in films) is to ensure that the characters are highly expressive to reinforce the spectators' "suspension of disbelief". It is necessary to create believable facial expressions to guarantee a correct perception of the character's emotions [Ekman and Friesen 1971]. Creating appealing and convincing facial animations is a laborious and time-consuming process that only expert digital artists are capable of doing. Our research deals with the necessity of simplifying and accelerating the creation of convincing facial expressions.

Usually, animators work with rigged 3D models. This process still involves heavy manual work, as the artists needs to manipulate the controls of a rig individually, in a discontinuous way, requiring them much working time to create believable results. The rig structure can easily become impractical as soon as the complexity of the characters and the number of expressions grow. Also, the diversity of facial models increase the difficulty when subtle facial details are needed, making each rig unique. Thus, the creation of an interaction model to intuitively manipulate the controls of a rig is not a trivial process; however, it would be an important technical advance, since current control systems remain unnatural.

3.2 Sketch Express Approach

This research deals with the manipulation of a facial rig. A rig can be a simple or a complex control structure (see section 2.1.1), depending on the movements we want to achieve in the 3D face. By requirement, the proposed approach should allow the user to control a rig through a continuous action and without the need of understanding its underlying structure. Furthermore, the control system should also allow (see Figure 3.1):

- *Facial Posing:* the user can intuitively create facial poses from scratch, by sketching strokes directly on the 3D mesh or on a virtual canvas.
- *Facial Animation:* the created poses can be interpolated resulting in real time animations.
- *Facial Retargeting:* additionally, the poses can be easily transfered to different models by storing the 2D strokes and later reusing them in different models.

The proposed system must be prepared for expert and non-expert artists creating complex facial poses with just a freehand drawing.

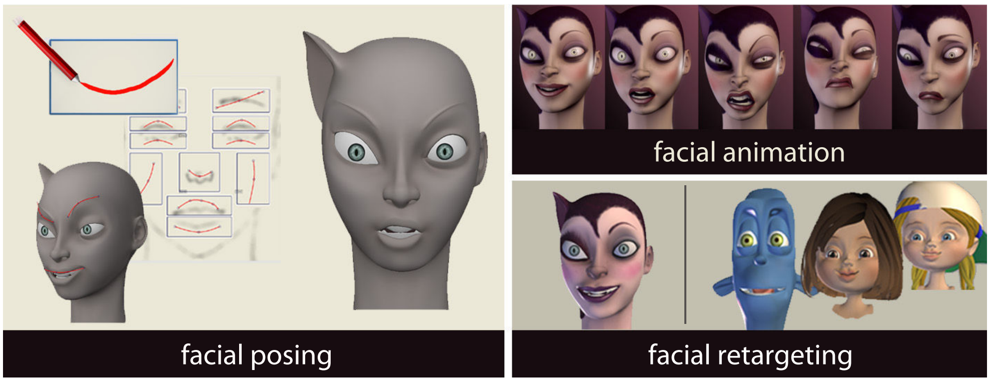


Figure 3.1: Facial Sketching Control System. left: the artist can draw strokes directly on the 3D mesh or on a virtual canvas to create facial poses; right up: the created poses can be used to generate facial animation; right down: one facial pose transferred from the cat-woman character to different target characters.

The rest of the chapter describes our proposal and the main problems we had to overcome.

3.3 Challenges

The main goal of this thesis is to create an interaction model that allows the animation of characters' faces on the fly. However, generating realistic face movements is a hard work because there are many subtleties to control, such as muscles behavior and wrinkles. Creating convincing and appealing facial expressions requires not only a deep understanding of the incredible complex system that lies beneath a face, but also a great knowledge of animation principals, in order to perfectly reproduce facial movements that look realistic. Our work gives special attention to the control interface for facial rigs. However, controlling a facial rig through sketching raises problems at two different levels, that are discussed in the following sections:

- The facial rig control.
- The interaction model based on sketching.

3.3.1 Facial Rig Control Problems

Facial animation is nowadays an important field in computer animation, continuously growing and strongly influenced by all previous body animation research [Orvalho 2007]. However, comparing the character face with the whole body, one can easily understand significant differences that should be taken into account.

First, a higher number of muscles is needed to create a facial expression more than to create a certain body pose. Moreover, the head cannot be animated with just a single joint like most parts of the body. In a face, the soft tissue simulation needs to be more realistic to capture all the subtleties of the facial expression. Lastly, it is not easy for an animator to achieve realistic results and overcome the expectations of human observers, who are experts at watching faces. It is easy for results to fall into the creepy appearance category known as the Uncanny Valley, first introduced by Masahiro Mori [Mori 1970]. Therefore, facial animation requires much more attention than body animation to obtain a lifelike response.

To obtain realistic results in facial animation, it is necessary to use a larger variety of deformers to simulate the soft tissue and muscles, to assign a greater number of joints to influence specific parts of the face and to implement a higher number of controls to manipulate the whole head structure and secondary face regions. Thus, to obtain good animations, it is necessary to have a facial rig with the right controls to reproduce any subtle movement of the face.

The manipulation of the rig controls is not, however, an easy task. Nowadays systems used to control facial rigs present some technological problems:

- *Many rig controls:* when defining a rig, artists tend to add many controls to handle every region of the face and reproduce the subtleties of each expression. Typically, they use *macro-controls* to manipulate major muscular groups that involve the whole face in large facial movements, and *micro-controls* for subtle movement that often appear only in one region of the face, such as the brows, eyelids or lips [Holly 2006]. When the number of micro and macro controls increases the process of rigging becomes difficult to master because there are an excessive number of controls to handle. Thus, encapsulating a set of rig controls on a single control usually simplifies the rigging process but presents a particularly challenging problem.

- *Discontinuous rig control:* generally, to handle facial rigs most systems require the manipulation of the rig controls in a discontinuous way, which means that the controls are handled one by one. Manipulating all the rig controls individually makes the process of rigging control time-consuming and difficult to master, specially in the regions of the face composed by many rig elements. However, handling several rig elements at the same time through a continuous action presents a challenging problem.

- *UI complexity:* typically, the interface to manipulate a rig is cumbersome because there are a lot of controls to handle. These rig's controls needs to be efficiently organized on the UI to become the usability natural and intuitive. Therefore, designing a rig's UI that intuitively maps the manipulation of the controls to the model deformation is extremely challenging.

3.3.2 Sketching Problems

Currently, sketch-based systems have undergone major developments. However, there still are some important challenges to be solved in this domain. Based on previous research [Olsen et al. 2009; Cook and Agah 2009; Cruz and Velho 2010], we present below some important open problems:

- *Drawing interpretation:* sketching is a natural and fast process for transmitting ideas. However, interpreting a sketch is not a simple task and ambiguity problems may be encountered. This is due to the fact that a stroke can have multiple interpretations. Therefore, the ambiguity problem inherent to freehand input is very challenging for ongoing research.

- *Lack of precision:* traditional WIMP interfaces, which uses a *control-point paradigm*, allows to accurately select and modify directly a surface vertex. On the other hand, sketch-based interfaces lose precision when trying to manipulate a 3D model, because they do not directly control the details of the surface. To enforce accurate precision in sketch-based systems it is normal to specify and infer geometric constraints. While mix input sketches with constraints is typical in engineering design systems [Jorge et al. 2003; Pereira et al. 2004; Contero et al. 2005], the same is not so common in other application areas, like free-form design systems. The meaning of a free-form stroke is hard to predict and, consequently, difficult to define geometric constraints. In these kind of applications, the geometric precision is less important than allowing the artist to create free-form strokes from freehand input and the precision is usually sacrificed in favor of the simplicity of the interface.

- *User interface:* One of the goals of sketch-based systems is to provide a natural interface that imitates the feeling of the traditional *pencil and paper* drawing. However, most sketch-based interfaces are far from being natural - many require the user *to draw in very specific ways* in order to function properly, which reduces the immersion and ease of use. Also, the fact of wanting such a clean interface can lead us to the problem of self-disclosure - when an interface does not disclose any hints about how to use it - raised by LaViola and Joseph [LaViola 2006]. Therefore, designing sketch-based systems with the correct combination of algorithmic and interface elements is a large challenge for ongoing research.

3.4 Sketch Express Overview

The system we propose implements a method that is independent of the underlying rig structure, being able to work with simple and complex rigs. We define a user interaction model that eases the control process of a 3D face based on a new approach (see figure 3.2).

The user can directly interact with the sketch-based User Interface tool (UI). The UI tool is represented by a sketching area where the artist can draw strokes to, consequently, create facial poses. The rig stores the control structure created by the artist. The UI tool is mapped to the rig using our sketching control method, which we call *SKC*. The *SKC* method applies a 3D geometric

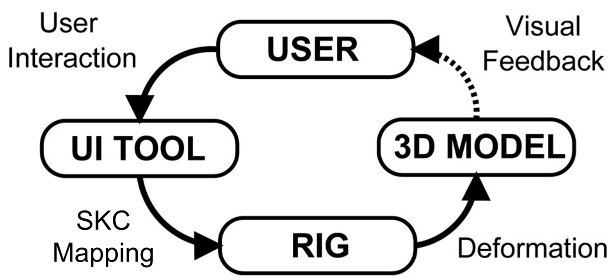


Figure 3.2: User Interaction Model

transformation on the rig structure based on the shape of the strokes drawn on the sketching area of the UI tool. The geometric transformation activated on the rig by the drawn strokes will correspond to the deformation of the 3D model. The user receives visual feedback of the deformation in a 3D viewport window.

Figure 3.3 shows an overview of the system pipeline and illustrates the facial sketching workflow.

We start with a rigged 3D facial mesh that is divided in several regions. The *mesh* is the external geometry of the 3D model. It uses a polygonal surface composed by a set of vertex and a topology that connects them. The *rig* is a highly deformable structure of a face and is created manually by an artist. The rig can be defined by several elements: joints, shapes, deformable objects and constraints. It is the responsible for triggering the deformation on the mesh. The *regions* represent specifics areas of the face, such as the brows, eyes, nose, cheeks or mouth. A region is defined as a set of rig elements (joints, for the sake of the explanation), which are manipulated by a stroke (see Figure 3.4).

There is an initial *setup* step to allow the user to define the facial regions that will be deformed. In the case of the UI tool to be composed by several canvases, the user needs to associate the defined regions to the corresponding canvases. The setup information ensures the mapping between the strokes will be drawn on the sketching area of the UI tool and the elements of the rig. Besides the setup stage, the regions can also be defined in real time during the sketching process.

After the setup step the 3D model is ready for the creation of facial expres-

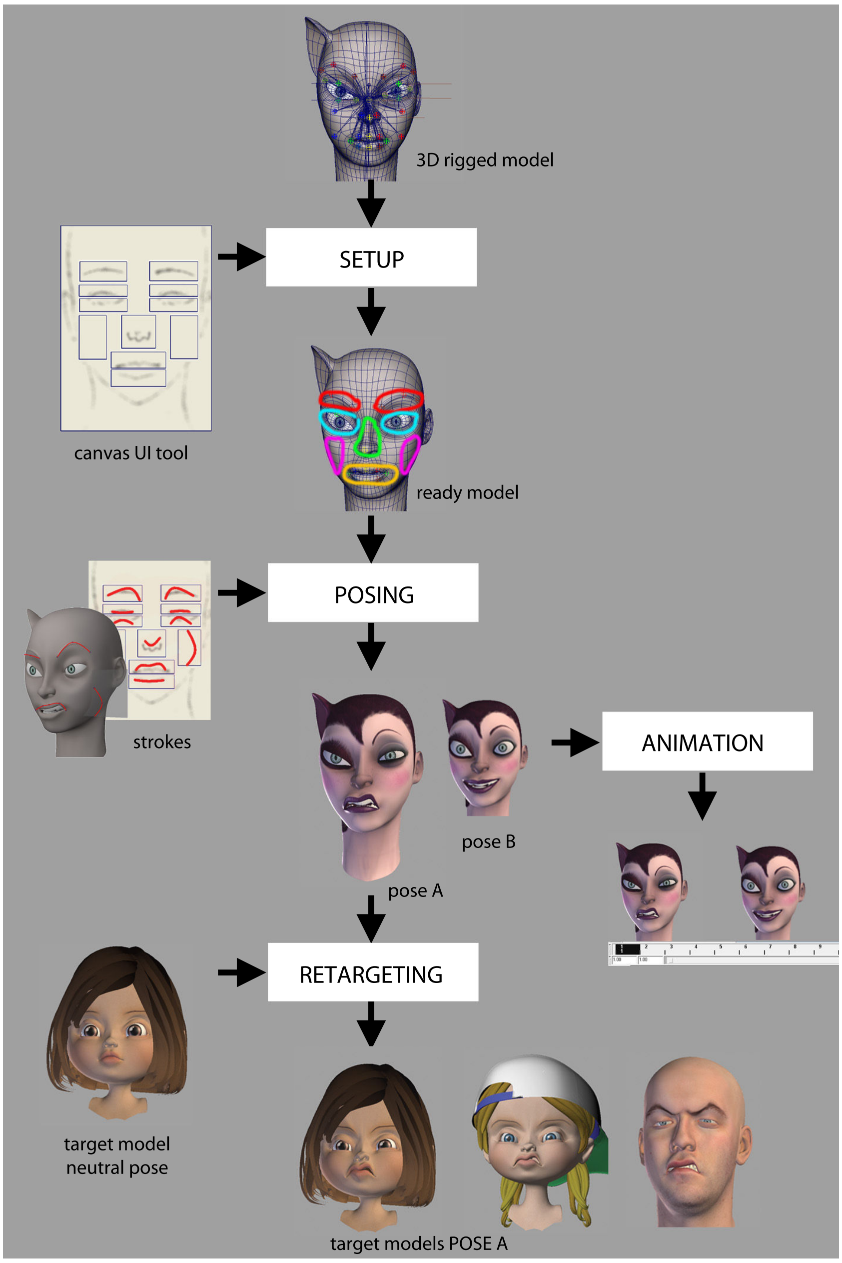


Figure 3.3: System Pipeline. Shows the main steps needed to create, animate and retarget facial poses with our facial sketching control system.

sions - *posing*. The user draws free-form strokes on the sketching area and the system automatically creates the deformation on the correspondent region of the 3D face, by the *SKC* method. The UI tool allows the user to draw strokes directly on the 3D mesh or on a virtual canvas. The user can indefinitely refine the strokes and save poses at anytime.

The created facial poses can then be used as keyframes for *animation* or transferred for different characters, by a *retargeting* technique. In this way,

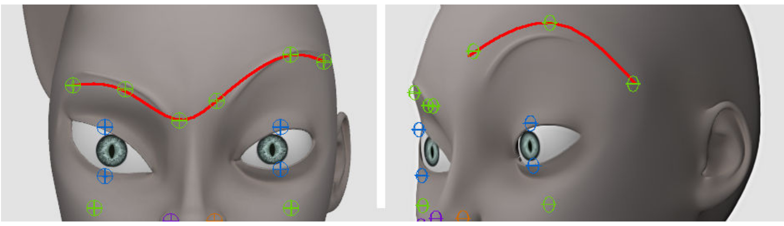


Figure 3.4: Sketching on the brow region on the 3D mesh. left: The stroke is associated to a region with six joints located on the left and on the right brow, the user deforms both brows with one stroke; right: The stroke is associated to a region with three joints located on the left brow, the user can only deform the left brow with one stroke.

the user can easily sculpt, retarget and animate facial expressions.

3.4.1 Innovation Issues

Although there are other approaches that use sketching to generate facial deformation, in this research we propose a system that presents some differences when compared to others, as we describe below:

1. We use sketching to control the structure underneath the 3D face - the rig, instead of deforming directly the mesh. Our approach decouples the rig from the mesh.
2. The rig must provide total control of each region of the face by manipulating the smallest number of controls as possible [Mucino 2004; Gorden 2005]. The developed method allows to encapsulate several elements of the rig in the same control of the interface. Therefore, with just a single control curve we can manipulate a large number of rig elements at the same time, solving the discontinuity problem presented nowadays in most rig control systems.
3. The developed method does not need to sketch two curves to apply a deformation, like the majority of the facial sketching systems do. With just one single curve we can define both the facial region that will be deformed as well as the shape of the deformation.
4. The developed method allows to deform the geometry with free-form sketching and the geometric precision is guaranteed by the underlying

rig. We provide a stable interaction, in which the system is able to detect erroneous input strokes and automatically fix them to a "‘possible"’ stroke. It does not mean that the stroke corrected by the system will produce the desired deformation, but it will surely produce a possible deformation for the defined rig. The potentiality of the method to work on the top of the rig decreases the ambiguity problem presented by many sketch-based systems.

5. The quality of the deformations to be achieved with our system depends on the rig quality. Therefore, if the rig quality is low, our method will still succeed, although the results of the deformation may not be satisfactory.

6. The approach we propose is not limited to a set of predefined curves with control points. Instead, our sketching method allows the user to draw continuously free-form strokes and change the stroke at any point, resulting in facial deformation on the fly.

7. The rig and the control interface often need to be updated to support new deformations. With our approach, the control interface always remains the same despite the modifications of the underlying rig. In this case, it will be just necessary to redefine the regions, accordingly to the new rig.

3.5 Sketching Control Method

For each stroke the user draws on the sketching area of the UI tool, the *SKC* method generates a NURBS curve. Then, it associates the curve to the corresponding region of the 3D model, causing a deformation of the 3D mesh.

The following section explains the main concepts related to the sketching representation and respective curve fitting.

3.5.1 Sketching Representation

We define a stroke S as an ordered set of points $\{s_0,..,s_{n-1}\}$, which is drawn on the sketching area of the UI tool. Each stroke S is stored as a parametric

NURBS curve N of *degree* $D = 3$. This curve helps the user do further editing to deform the 3D model. The curve N is parameterized with t edit points, where t corresponds to the total number of joints that belong to the same region K of the 3D model (see Figure 3.5).

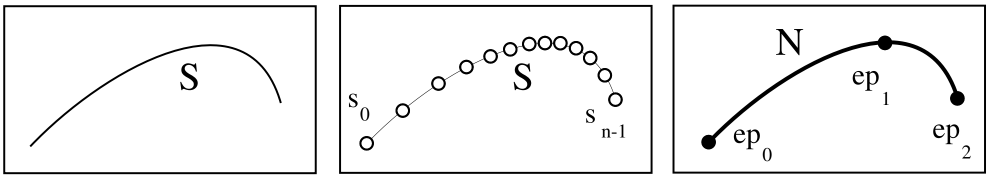


Figure 3.5: NURBS curve N generated by the input stroke S; left: input stroke S; middle: sequence of point samples $\{s_0,..,s_{n-1}\}$ *that define S. Notice that the samples are spaced irregularly, depending on the drawing speed; right: creation of the NURBS curve with three edit points* (ep_0, ep_1, ep_2)*. This curve corresponds to a region rigged with three joints.*

The number of *knots* required to create a NURBS curve is $2D + M - 1$, where M is the number of spans. In our system, the curves are created by defining a set of t edit points. Therefore, the number of knots required is $2D + t - 2$ ($M = t - 1$). When an edit point is moved, it is not the edit point that changes. Instead, the control vertex that influence the edit point is moved. An edit point is therefore an intuitive mean of altering the curve by indirectly moving control vertices.

In the current version of the system, we do not take advantage of the *weight* parameter to create the curve. All the created curves are non-rational, therefore, all weights are equal to 1. However, this can be a possible future extension, in order to develop a correspondence between the joints' weight and the curve's weight.

The method generates the curve N by choosing the edit points ep_i along the total number of points, n, of the original stroke S:

$$ep_i = S\left(\frac{i*(n-1)}{t-1}\right) \qquad i = 0,..,t-1 \qquad n > t \tag{3.1}$$

It is necessary to compute at least three edit points to generate the curve. Each ep_i has associated one joint j_i by region K. In case the region K has only one joint, the method will consider the middle edit point; in case of two joints, it will consider the first and the middle edit points.

We do not resample the points of the original stroke *S* because we want to take advantage of the natural way of drawing. As it was already mentioned in Section 2.4.1, the points of *S* become irregularly spaced, since the user does not naturally draw with the same speed (see Figure 3.6 left). Thus, as shown in Figure 3.6 right, smoothing the original points to have an uniform spatial redistribution can destroy the shape of the stroke drawn by the user.

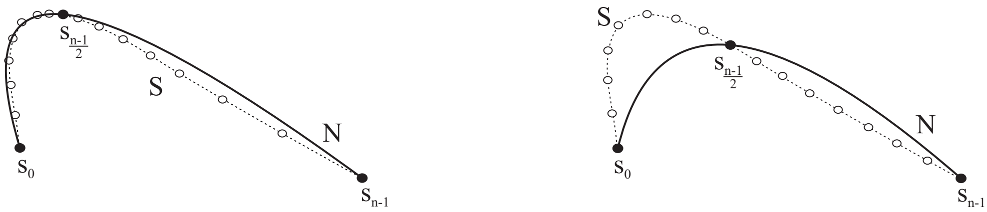


Figure 3.6: Curve fitting; the input stroke S (dashed line) and the curve N generated with $t = 3$ *edit points (full line) computed through the Equation 3.1; left: without resampling; right: with resampling; Notice that the fitting without resampling generated a curve with the shape closer to the input stroke.*

The fact that the curve *N* is parameterized with the same number of joints that belong to the region *K* allows a stroke *S* badly drawn by the user to be automatically "corrected"' by the system (see Figure 3.7). It means that the *SKC* method will adapt the stroke drawn by the user to the rig defined by the artist, diminishing, in this way, the problem of ambiguity presented by most of the sketch-based systems.

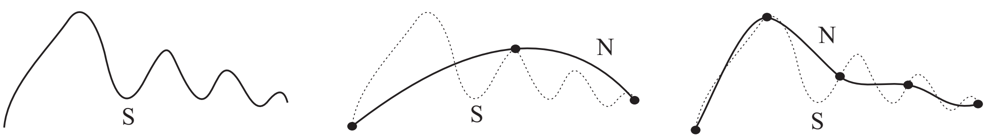


Figure 3.7: Curve generated by the system from an erroneous stroke *drawn by the user; left:* erroneous stroke *S; middle: the curve N corresponds to a region rigged with three joints; right: the curve N corresponds to a region rigged with five joints.*

Figure 3.8 shows two strokes around the mouth converted into two NURBS, and the resulting deformation on the face model. It is worth to highlight the advantage of manipulating several joints simultaneously just with a simple stroke. By doing it, the problem of discontinuity presented by many rig control systems is solved.

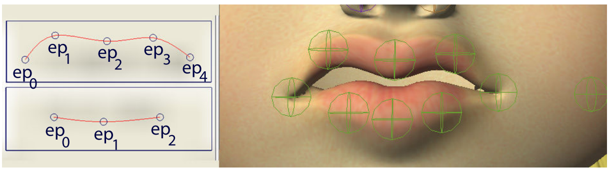


Figure 3.8: Close-up of the mouth region. Notice how the mouth deformation are accordingly to the shape of strokes; left: two strokes around the mouth; the NURBS of up stroke created with 5 ep_i because the mouth up region has 5 joints; the NURBS of down stroke has 3 ep_i because the mouth down region was rigged with 3 joints; right: correspondent mouth deformation.

The *SKC* method developed in this thesis allows to manipulate a rig structure through simply 2D sketching. As the user can draw strokes directly on the 3D mesh or on a virtual canvas, we divide the *SKC* method in two components:

- *Sketching on the 3D mesh*, to compute the geometric transformation of the rig elements based on the shape of the strokes drawn directly on the 3D mesh.
- *Sketching on the virtual canvas*, to compute the geometric transformation of the rig elements based on the shape of the strokes drawn on the virtual canvas.

3.5.2 Sketching on the 3D Mesh

The user draws a stroke S directly on the mesh to control a certain region K of the 3D model.

The method begins by duplicating the original 3D mesh. We name the original mesh Active mesh A_m and the duplicate Reference mesh R_m. We hide R_m and use it only as a local coordinate reference. The mesh that will be deformed is A_m.

The method performs ray casting with the stroke to choose the closest points on the Reference mesh R_m (see Figure 3.9).

For each stroke drawn on the mesh R_m, the method updates the joints' positions of the respective region K of the 3D model. To know which region K

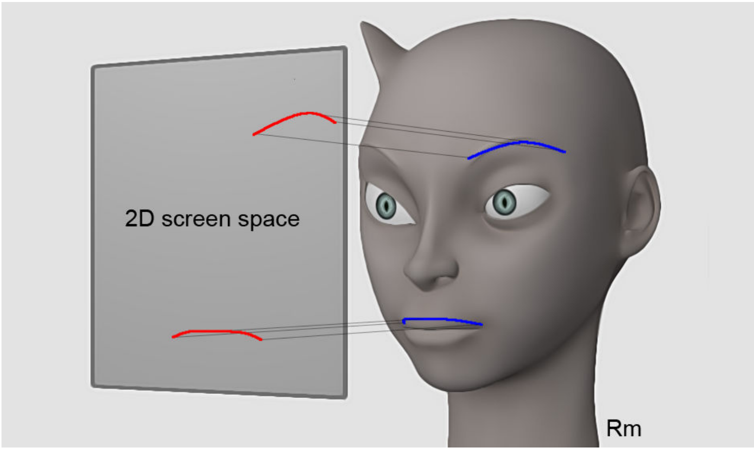


Figure 3.9: A stroke is drawn on the screen plane and projected onto the mesh R_m by ray casting techniques.

will be controlled by the stroke S, we only need to compute the closest joint of the first point of the stroke s_0 The distance $dist_i$ between s_0 and joint j_i is given by the Equation 3.2, where s_0 is the first point of S projected on the mesh R_m, $nJoints$ is the total number of joints of the rig and j_i is the position of each joint.

$$\forall_{i<nJoints} \qquad dist_i = \|s_0 - j_i\| \tag{3.2}$$

The joints that belongs to the same region K of the closest joint are the joints that need to be updated. The new position of each j_i of the closest joint's region will update the mesh A_m with the same coordinate of the correspondent ep_i of the curve N ($j_i = ep_i$). Thus, drawing strokes on the 3D mesh always implies a tangent deformation on the surface, i.e. the deformation is automatically constrained by the surface. The main advantage of sketching directly on the 3D mesh is that it is view-independent, because it allows the user to draw strokes from any viewpoint direction.

3.5.3 Sketching on the Virtual Canvas

The user draws a stroke on a virtual canvas to deform the associated region of the 3D model.

Canvas. The canvas C is a 2D drawing area where the model deformation can be sketched on. There are two types of canvas: *2D canvas* and *2.5D canvas*. The 2D canvas is predefined on the UI and it has a fixed position, size and orientation. The 2.5D canvas is a dynamic screen-aligned billboard created in runtime, always perpendicular to the user viewpoint direction [Akenine-Möller et al. 2008]. The shape and position of a stroke affects the associated rig elements in the 3D model. Thus, the combination of stroke and canvas becomes the effective controller of a region of the 3D model. This model is a 3D face displayed on a separate area, which we call deformation space *B*.

Deformation Space. The deformation space *B* shows, in real time, the correspondent deformation of the 3D model. To compute the deformation space *B*, we calculate the minimum bounding space of the actual joints position, obtaining the minimum and maximum position values r_0 and r_1 (see Figure 3.10 first row).

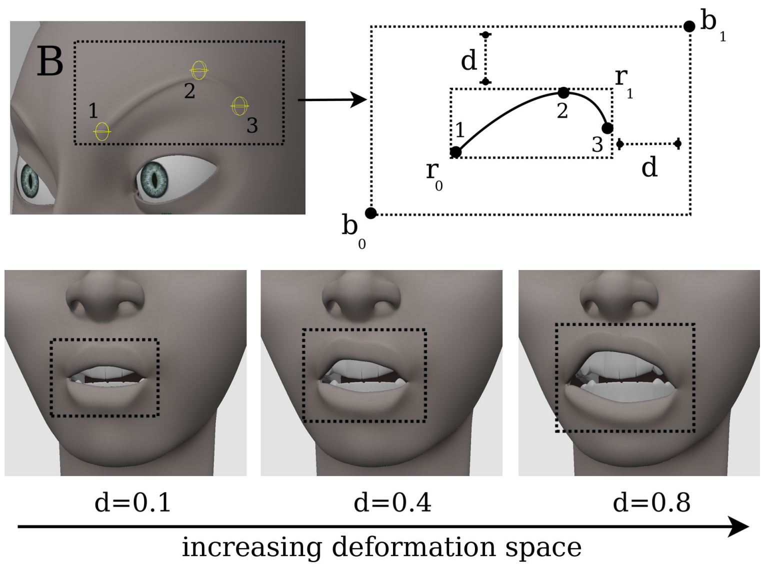


Figure 3.10: Deformation Space B; first row: deformation space B where the joints movement take place, the initial position of the joints are represented by highlighted circles; The value d represents the displacement to expand the deformation space; second row: close-up of the mouth region with different d values on the xy coordinate; Notice that the deformation space increases from left to right.

To allow the joints to move "outward" of their actual position, but also to support exaggeration of deformations, we expand the space by a displacement value d. This value is initialized by the system, but also can be updated by the user in real time, accordingly to the deformation weight he wants to achieve. If d increases the deformation space will expand. This is crucial for certain models, like cartoon style characters, in which it is often necessary to exaggerate certain regions of the face. Thus, if d decrease the deformation space will shrink. The points b_0 and b_1 are the deformation space limits, which are defined as:

$$\begin{aligned} b_0 &= r_0 - d \\ b_1 &= r_1 + d \end{aligned} \tag{3.3}$$

Figure 3.10 second row shows a close-up of the mouth region with different displacement values and consequently different deformation spaces.

Sketching on 2D canvas

Based on the above definitions, we additionally define a 2D domain, represented by the 2-tuple (N,C), where N represents the curve generated from the stroke S, and C is the 2D canvas that contains it. Similarly, a 3D domain is defined as a 2-tuple (K,B), where K represents the region of the 3D model, and B is the deformation space. The relationship between the 2D and 3D domains, defined by the method *SKC*, determines the correspondence between the tuples (N,C) and (K,B) (see Figure 3.11).

We split the *SKC* method in two stages:

1. using an affine mapping M as our kernel function, we compute the xy-coordinates of the joints to obtain the XY plane deformation.

2. then, through ray casting techniques, we find the value on the z coordinate to obtain the deformation along the Z axis.

Stage 1: XY-Plane Deformation. The method starts by computing the xy-coordinates of the rig's joints. The rectangular window correspondent to the canvas C is mapped to the corresponding rectangular window of the deformation space B, by axis-aligned, non-uniform scaling. The method computes the mapping between the curve edit points ep_i and the correspondent joints of the associated region K. The new position of the joint j_i on the XY plane deformation is defined by:

$$j_i = a * ep_i + f, \qquad i = 0,..,t-1 \tag{3.4}$$

where:

$$\begin{aligned} a &= (b_1 - b_0)/(c_1 - c_0) \\ f &= b_1 - c_1 * a \end{aligned} \tag{3.5}$$

The points c_0 and c_1 define the limits of the canvas space.

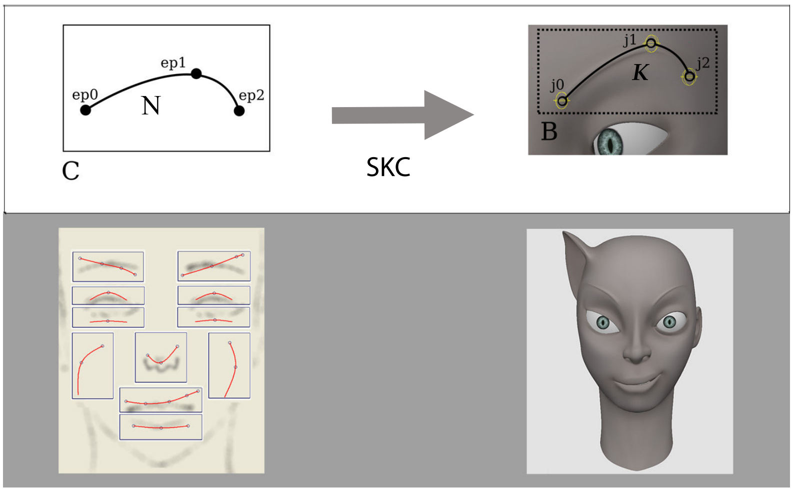


Figure 3.11: Sketching on predefined 2D canvas; up row: The method SKC *compute the mapping between the canvas C and the curve N with the deformation space B and the region K; down row: 3D model deformation based on the strokes drawn on the 2D canvas.*

Stage 2: Z Axis Deformation. So far, the method has only changed the x and y coordinates of the joints, but to obtain a 3D deformation, it needs to change the values on the Z axis. To constraint the movement of the joints to the 3D model mesh, the method compute a tangent deformation over the surface by adjusting the z coordinate of each joint j_i.

The tangent deformation is based on ray casting, and it is an adjustment over the reference mesh R_m (see Figure 3.12). In A_m, the joint j is moved from its initial position j_0 to position j_1 by the affine mapping M. To change the joint coordinate and get to the final joint position over the R_m, the method calculates the auxiliary point p_{aux} in front of the mesh by adding the joint position j_1 to the normal vector on the mesh $\vec{n}$:

$$p_{aux} = j_1 + \vec{n} \tag{3.6}$$

Then, it casts a ray $\vec{r}$ from p_{aux} in the inverse normal direction. The intersection point between $\vec{r}$ and R_m is j_2, the final position of the joint with the xyz coordinate computed.

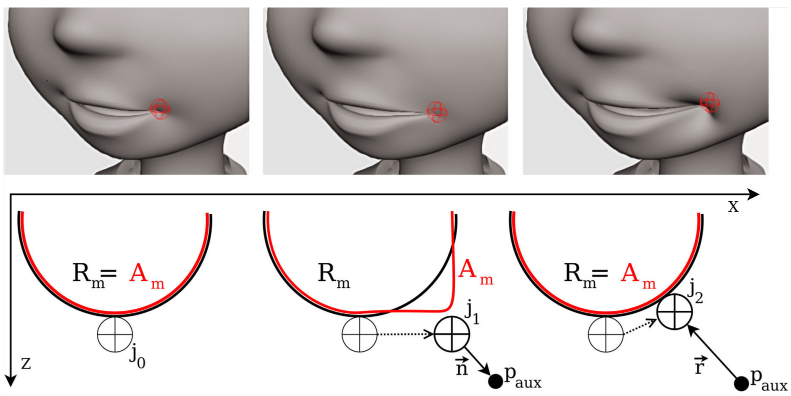


Figure 3.12: Tangent deformation over the surface; first row: close up of the mouth region; second row: 2D representation of the deformation steps; left: j_0 is the initial position of the joint; middle: j_1 is the position after the mapping M, which is not tangent to R_m; right: the final joint position j_2 is calculated according to j_1, normal vector $\vec{n}$, point p_{aux} and the ray $\vec{r}$ cast from it.

The 2D canvas configuration is view-dependent. Thus, the only controllable re-posing action is a translation orthogonal to a fixed viewing plan, followed by automated depth tweaks. The user cannot rotate the camera to apply, for example, deformations that come out the mesh, like bulges. To overcome this limitation and to allow the creation of "non-tangent" deformations, it was created another type of canvas: the 2.5D billboard canvas.

Sketching on 2.5D canvas

The user draws strokes S on a 2.5D canvas to deform the associated region of the 3D model. The user interaction takes place on a 3D space, where the 3D model is located. There are no predefined canvas like in the *sketching on 2D canvas*.

The 2.5D billboard canvas can be created in two different ways:

- by the user, which can place the 2.5D canvas in any position of the 3D scene at any time; In this case, the created canvas needs to be associated to the region K that the user intends to deform.
- automatically by the system, when the system recognizes that a stroke comes out of the mesh; In this case, the new canvas is immediately associated to the same region K of that stroke.

We extended the affine mapping M by computing a transformation between two bounded boxes in 3D space, instead of computing a transformation between two 2D rectangular windows. The upper row of Figure 3.13 shows the canvas bounding box that is mapped to the correspondent deformation space bounding box.

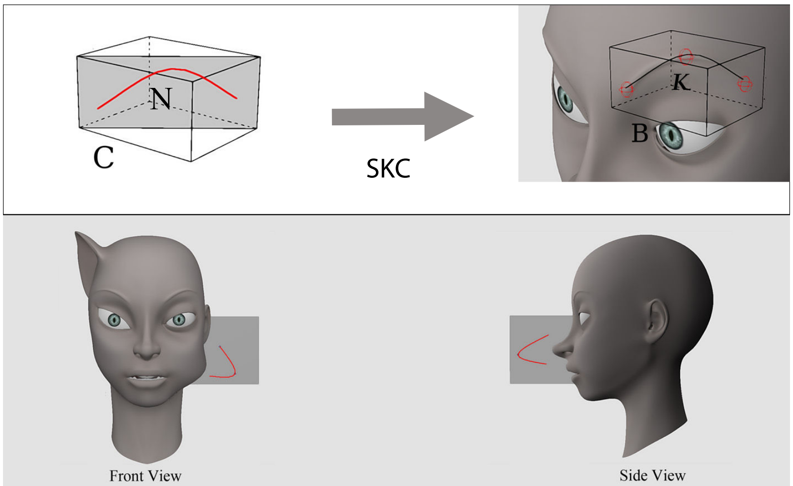


Figure 3.13: Sketching on 2.5D canvas; upper row: the method SKC *compute the mapping between the bounding box C and the curve N with the deformation space B and the region K; lower row: deformation of the cheek and nose using a 2.5D canvas.*

Any stroke on the 2.5D canvas will imply a 3D deformation in a parallel direction to the canvas plane (see Figure 3.13, lower row). The principal reason of the 2.5D canvas is to allow the user to create non-tangent deformations, like the bulges showed in the figure. In these situations, it is not necessary to constrain the movement of each joint j_i to the 3D mesh and the stage 2 of the *SKC* method is not necessary to be executed.

Figure 3.14 illustrates the possibility of applying the same displacement to several joints of the same region K. To compute the displacement vector $\vec{d}$, we only consider the midpoint ep_i of two successive curves N_j and N_{j+1}:

$$\vec{d} = ep_{(i,N_{j+1})} - ep_{(i,N_j)} \tag{3.7}$$

Finally, $\vec{d}$ is applied to all the joints that belong to the region K:

$$j_i = j_i + \vec{d} \tag{3.8}$$

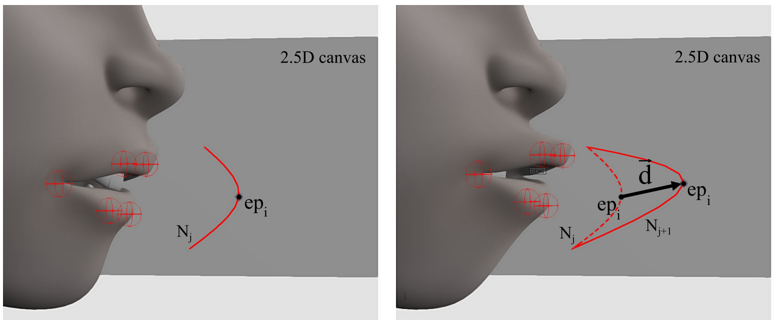


Figure 3.14: Displacement of the joints of the mouth region. left: joints position defined by N_j; right: joints position defined by N_{j+1} after a displacement was applied to each joint. Notice thal all the joints of the mouth moved in the same direction of the displacement vector $\vec{d}$.

3.6 Sketch Express Framework

We use the *SKC* method to build a sketching control system for facial animation. We developed two different interaction models:

- *2D Sketching Interface*, which allows the user to draw strokes on a fixed 2D canvas (see Section 3.5.3).
- *3D Sketching Interface*, which allows the user to draw strokes on both the 3D mesh (see Section 3.5.2) and the 2.5D canvas (see Section 3.5.3).

The system is implemented in C++ as a plug-in for Maya, chosen for prototyping purposes. It is composed by four modules: Setup, Facial Posing, Facial Animation and Facial Retargeting, that are described in the following sections.

3.6.1 Setup

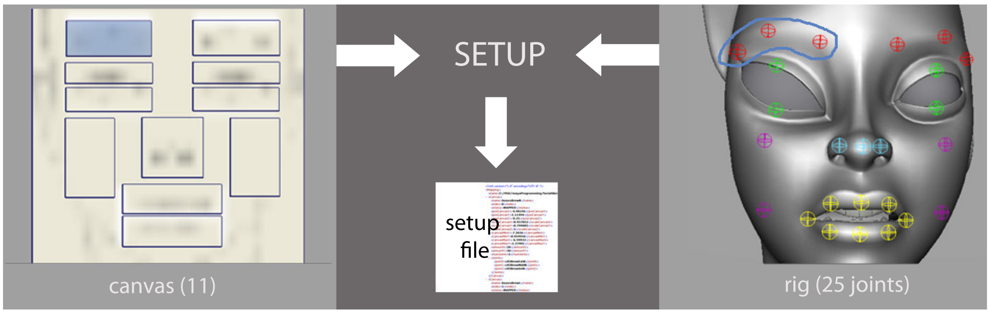


Figure 3.15: Setup Module Overview.

This is the initial step, where the user defines the regions of the rig model (see Figure 3.15 right), which will be manipulated by strokes. In the case of the *2D sketching interface*, the defined region also needs to be associated to the corresponding canvas of the UI tool (see Figure 3.15 left). We have implemented a wizard interface to assist the user on the setup process, hiding the complexity of 3D modeling and animation. The wizard is prepared so novice users can also configure the system. Additionally, the defined regions can be saved in a XML setup file (see Figure 3.15 middle). Thus, characters with a similar rig can use the same file. For example, in a production with 10 different characters that share the same rig, the setup needs to be performed only once. For a new character with a different rig, we either do the setup process or apply a rig retargeting technique [Orvalho 2007; Komorowski et al. 2010] and then apply the stored setup file. The character of the Figure 3.15 has 25 joints and it took about one minute to setup the rig to the 11 canvas. After the setup step, the 3D model is ready for the creation of facial poses and animation.

3.6.2 Facial Posing

To create a pose the user needs to deform the face model. Deforming the mesh of the face model is a very straightforward and interactive process. First, the user draws a stroke on the drawing area of the UI tool. Then the stroke is mapped into the 3D model, which automatically deforms the correspondent facial region of the character. The user can continue drawing strokes to interactively sculpt poses. The user can also modify an existent stroke (totally or partially) and adjust the shape of the mesh in real-time.

The user starts by deciding which sketching interface to use: *2D Sketching Interface* or *3D Sketching Interface*.

2D Sketching Interface. Sketching on a 2D Canvas neatly maps the mental concept of a face as a collection of parts. Each part is a facial region, such as, the brows, eyes, nose, cheeks and mouth. We start with a sketching area located in the 3D space. This drawing area is composed of several canvases, which are depicted as boxes on the background generic face image (see Figure 3.16 left).

Figure 3.16: 2D Sketching Interface*; left: 3D model deformation based on the strokes drawn on the 2D canvas; right: two examples of how the user can draw the strokes guided by the background image.*

The user can load different background images to use as a reference (see Figure 3.16 right). For artists changing the background image to reflect each expression they have to generate helped the process of mapping the 2D drawing with the 3D final pose. Each canvas represents a different facial region of the 3D face model. These regions are enabled every time the user draws a stroke, which automatically deforms the 3D face mesh, through the *SKC* method.

Figure 3.17 illustrates a set of facial poses in three characters with different styles (cartoon child, fantastic creature and realistic man). These models share the same rig structure, therefore the setup was created only for one model.

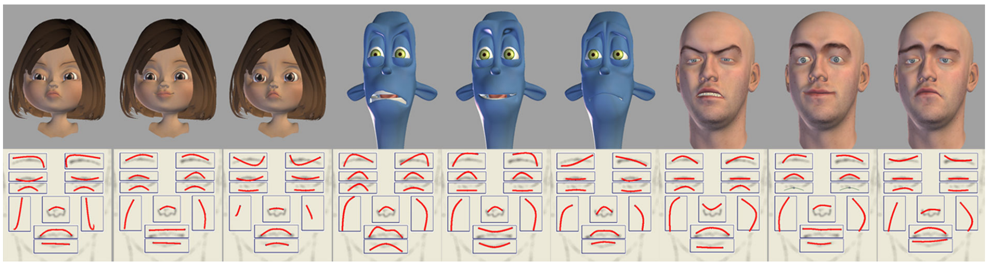


Figure 3.17: Facial poses created using the 2D canvas approach; top row: 3D models; down row: the strokes draw on the 2D canvas generated the facial pose of the correspondent model.

3D Sketching interface. The 3D sketching interface combines the components of the *SKC* method: it allows the user to sketch directly on both the 3D mesh and the 2.5D canvas (see Figure 3.18 left).

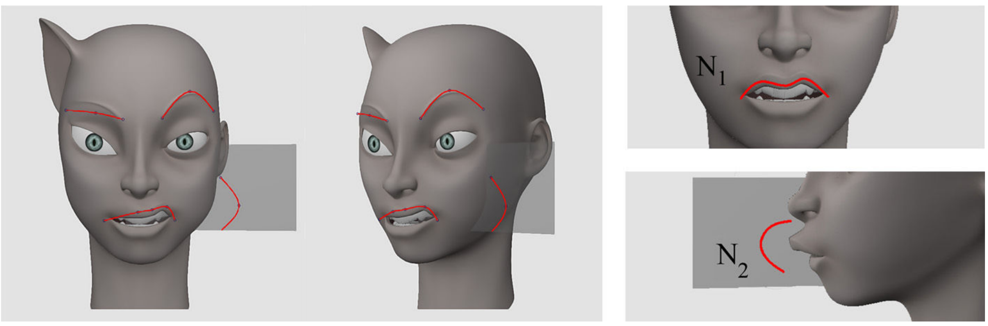


Figure 3.18: 3D Sketching Interface*; left: sketching on both the 3D mesh and the 2.5D canvas; right: multiples curves deforming the same region; curve N_1 drawn on the 3D mesh changes the shape of the mouth; curve N_2 drawn on the 2.5D canvas pulls the mouth. Notice that two curves never overlap in the same region.*

The user interaction takes place on the 3D space, where the 3D model is located and there are no predefined drawing area like in the *2D Sketching interface*. The 2.5D billboard canvas is created on the fly and the user can draw strokes from any camera orientation, which facilitates the work around the 3D space.

In Figure 3.18 right, we show an example of multiple curves deforming the same region. Notice that there is only one curve visible in the mouth region at each time. When the user sketches a new stroke the previous curve is deleted to avoid that the curves overlap in the same region.

Figure 3.19 compares the sketching interface modes: direct drawing over a 3D mesh, 2D and 2.5D sketching on a canvas. The results show the possibility of using the 2.5D approach, like bulges in the face or stylized and cartoonist noses (such as Pinocchio's), which are not possible in the 2D approach. It also demonstrate how it is possible to draw strokes directly on a 3D face model and still maintain the morphology of the face. This is feasible because the movements are constrained by the mesh, avoiding the geometry to do unexpected deformations outside the 3D face model. Combining the 3D direct manipulation and the 2.5D canvas allows to go around the limitations associated to the 2D canvas interface.

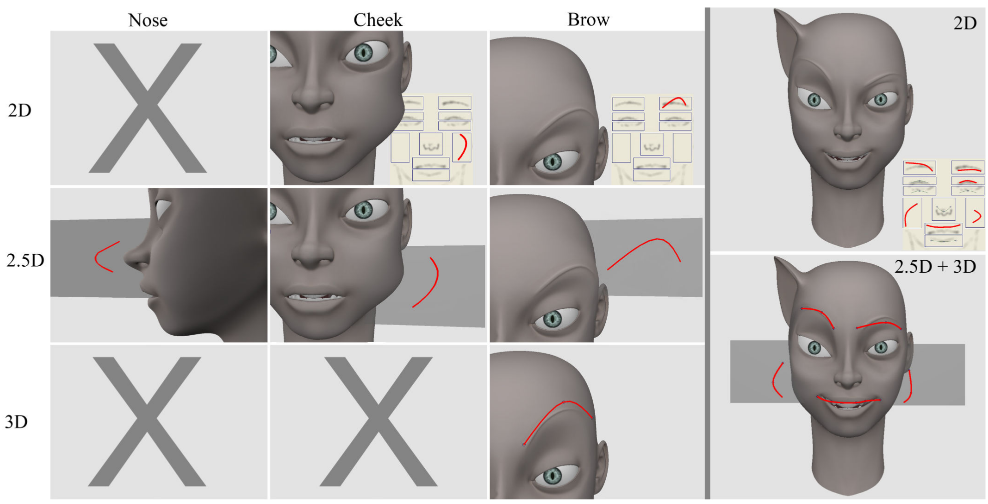


Figure 3.19: Comparison of facial poses using the different UI configurations of our sketching method. The box with an X means that the expression is not possible to achieve with that UI configuration; right: two facial examples using the 2D canvas interface and combining 2.5D canvas and direct sketching over the 3D mesh.

3.6.3 Facial Animation

As an add-on to our sketching system we allow the user to create facial animations using the traditional keyframe technique. Our system is designed having in mind the usability and direct manipulation. After creating all the facial poses the user is able to generate animations by interpolation of poses. Figure 3.20 shows a few frames of a facial animation sequence obtained using our sketching system and generated with off-line render.

Figure 3.20: Keyframes extracted from a video sequence to show different poses created using our method; final results generated with an off-line render.

3.6.4 Facial Retargeting

By facial retargeting we mean the action of transferring the facial pose from a source to a target model. The mesh topologies of both source and target models can be different but the rig structure must be the same.

In our system to retarget facial poses we store, in a *pose* file, the strokes the user draw in the canvases (see Figure 3.21). For each stroke drawn on the canvas, we save the edit points ep_i used to generate the curve N, and the displacement value d used to compute the deformation space B (see Section 3.5.3). Then, these data can be reused in different characters as long as they share the same rig. After the curves are loaded into the new 3D model the user can use the sketching tool to delete, modify and re-draw the curves to create new poses, or simply modify the d value to adjust the weight of the deformation.

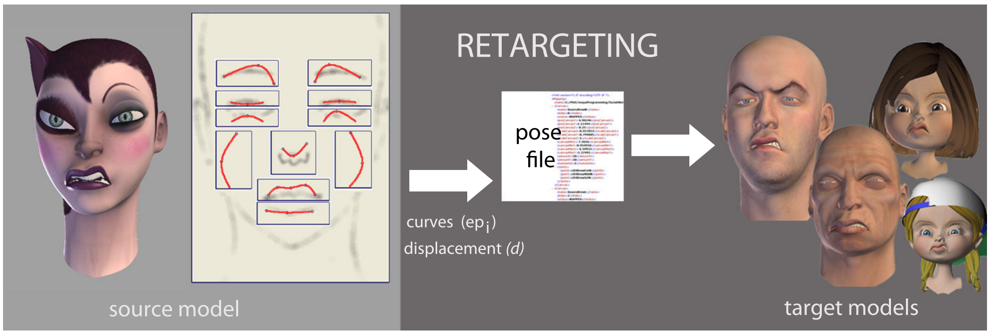


Figure 3.21: Retargeting from a source model to different target models. Notice that the characters have different facial proportions and styles.

Figure 3.22 illustrates the retargeting of facial poses between different models. The first column shows the strokes in the canvases; column 2 shows the source model with the pose created with the strokes from column 1, while columns 3 to 7 show the result of the retargeting process. Each row represents a different source model and shows how the retargeting results vary between characters but retain consistency. Notice that when the source and target characters have similar facial proportions the retargeting result is accurate. However, if the facial proportions vary significantly, the retargeting process may produce exaggerated deformations. Figure 3.22 row 4 shows an example of how the deformation in the mouth breaks for extreme poses. The user can fix the pose by modifying the curves or simply by adjusting the displacement value d (see Figure 3.22 row 5).

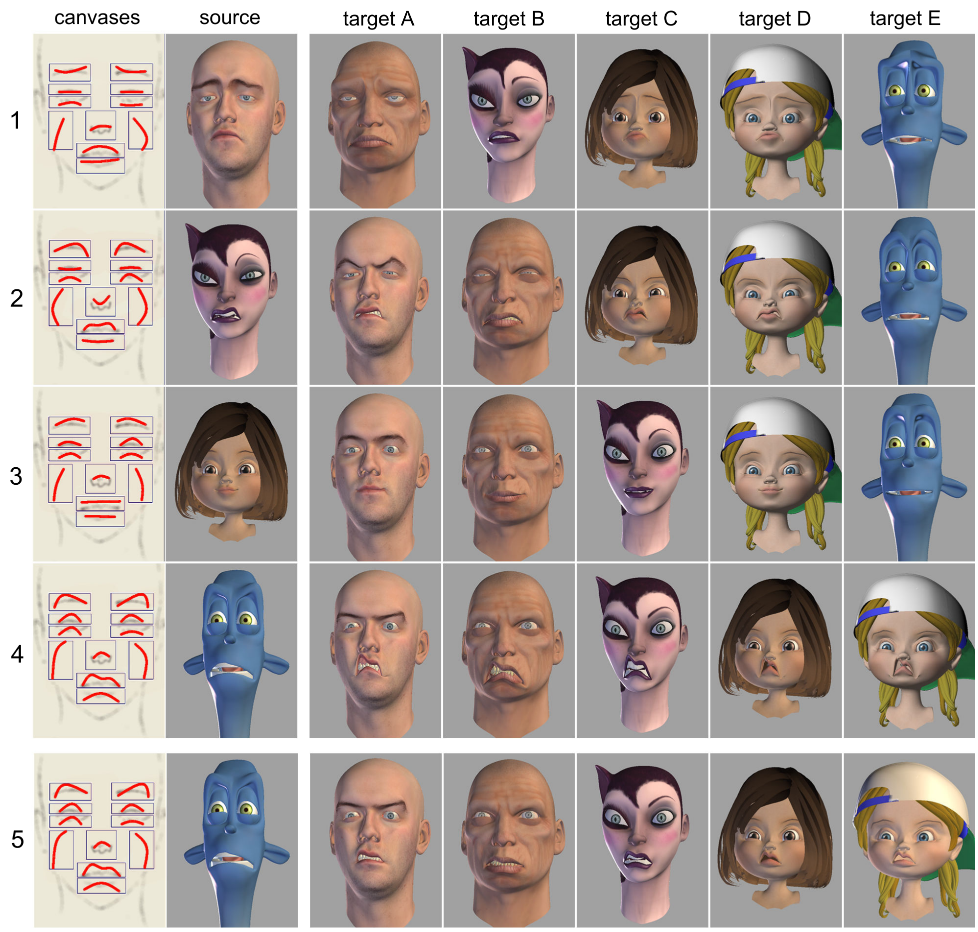


Figure 3.22: Retargeting. Rows 1 to 4 show the retargeting of characters with different facial proportions. Row 4 is the most extreme case of retargeting as the source model proportions are very different from the rest of the characters. Thus, the expression on the target characters breaks the mesh (see mouth region). Row 5 fixes the poses by adjusting the deformation window.

Chapter 4

Results and Validation

The facial sketching control system *developed in this research was validated with a series of experiments. We made several computations in order to quantify the user's effort and the time the user took to create a pose. To evaluate if the poses created can be automatically transferred to different models we tested the precision of our retargeting method. We also underwent tests to measure the response time of the system. The 3D facial models used during the experiments were created by artists, who have supervised the results and provided valuable feedback to improve the workflow of the system. The results from our research also were applied in the psychotherapy field. The developed sketching method is implemented in a serious game context, where the goal is to teach people with autism to recognize emotions from facial expressions. At the end of this chapter, you can verify that the proposed approach allows to produce facial expressions in an easy, fast and intuitive way.*

4.1 Introduction

Central to the research work presented in this document is the validation step, since we need to know if our sketching approach is a valid method to create facial expressions. The work includes two different interaction models to create facial expressions: a 2D interface, which allows the user to draw strokes on a 2D canvas, and a 3D interface, which allows the user to draw strokes directly on the 3D mesh or on a 2.5D billboard canvas. We want to evaluate which one is the easiest, more intuitive and the quickest interaction method to prototype facial expressions. We also make some comparisons with traditional rigging techniques, where the user manipulates directly each element of the rig.

To test the system, we used face models with photorealistic, cartoon and fantastic style that were created by artists (see Figure 4.1).

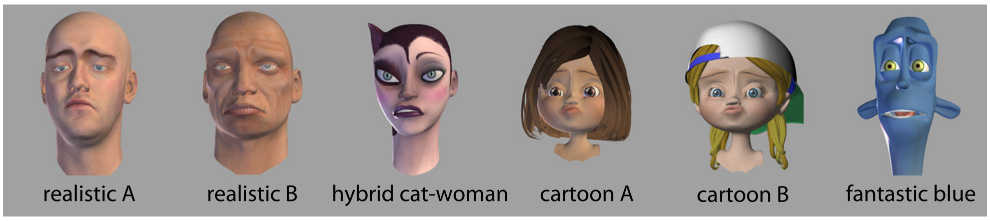


Figure 4.1: We tested the system with six different characters: two realistic man, one asymmetric hybrid cat-woman, two child cartoons and one alien-like fantastic creature.

Our sketching system can handle symmetric and asymmetric characters and is independent of the underlying rig structure. For example, the asymmetric cat-woman took about 7 days for modeling and texturing and about 5 days to define the rig structure. Our system does not aim at speeding up this part of the process, but only the animation once the models have been created following standard pipelines.

The system was tested with rigs of different complexity (see Figure 4.2). It works with any type of rig elements whose control points can be moved in 3D space, such as joints, FFD objects or NURBS surfaces. If the rig is composed by blendshapes it is necessary to make a pre-process, since the blendshapes do not have a correspondent position to directly move in the 3D space. The blendshapes are usually interpolated through sliders. This pre-process is crucial to map each blendshape to another control object with a physical position in the 3D space. For example, the open eye shape is bound to a control joint in a upper position and the closed eye shape is bound to the same control joint but in a lower position. Then, when this control joint is moved from the upper to the lower position, the shapes are interpolated and the eye closes. The developed sketching method works with blendshapes in this indirect way. In our system there are no restrictions about the number of joints neither on their placement on the mesh. We tested rigs that have between 25 to 39 joints and rigs with about 56 shapes, which are controlled by 14 new control joints.

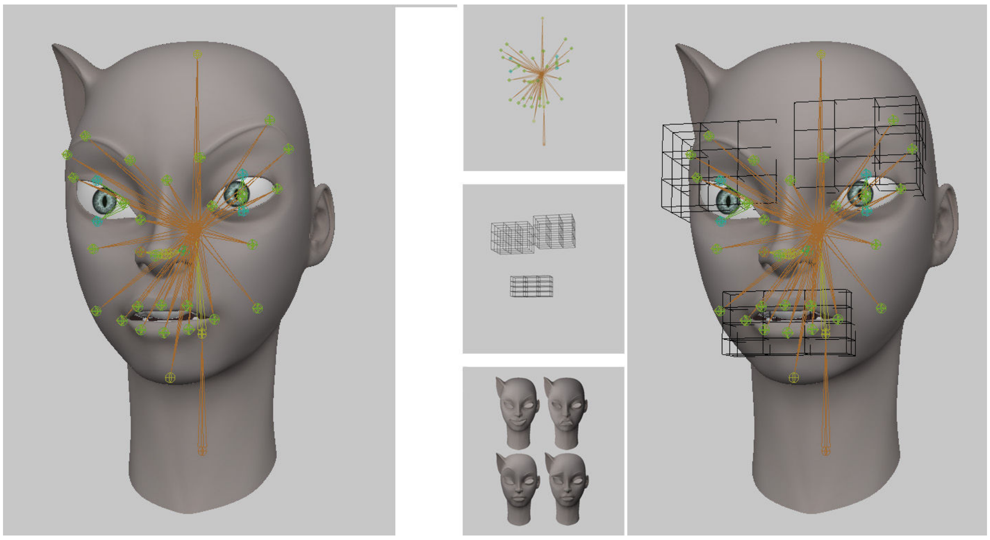


Figure 4.2: Rigs with different complexity; left: a simple rig based only on a highly articulated facial skeleton, composed by 33 joints; right: a complex rig based on joints, shapes and lattices to provide additional deformation in the brows and mouth regions.

We have carried out two different experiments. In the first experiment, which we call *Facial Posing Experiment*, we tested the usability and the performance of the sketching method, by measuring the user's effort (number of clicks, curves created, modified and deleted) and by computing the time the user took to create a pose. In the second experiment, which we call *Facial Retargeting Experiment*, we tested the accuracy of our retargeting method. The idea is to evaluate if a source model expression can be accurately reproduced on different target characters. We also performed a test to measure the response time of the system, which we call *Performance Test*. Finally we present LIFEisGAME, a *Case Study for Therapeutic Purposes*, which benefits from the core method developed in this research.

4.2 Facial Posing Experiment

This experiment was designed in order to evaluate the effectiveness of our facial system. It reveals if our sketching interaction models are valid to create facial expressions. It also evaluates how comfortable artists feel in incorporating these models in their production pipeline. We compared our control system to traditional rigging techniques, where the user manipulates directly the individual controls of the rig. We consider our sketching interaction models more natural and intuitive to users than the traditional technique. Therefore, we have formulated the following four hypotheses for this experiment:

- H1: Our sketching interaction models are easier and more intuitive to create facial expressions than the traditional technique;
- H2: The 2D sketching interface reduces the user's time to create facial expressions when compared to the traditional technique;
- H3: The 3D sketching interface reduces the user's time to create facial expressions when compared to the traditional technique;
- H4: It is easier and more intuitive to deform the model by drawing strokes on a 2D canvas than drawing strokes directly on the 3D mesh;

The user's effort (H1) was evaluated through the answers collected in a questionnaire related to the usability of the three interaction models: 2D sketch-approach, 3D sketch-approach and traditional-approach. The time to create facial expressions (H2,H3) was validated by objective quantitative measurements, since we recorded the average time users took to create a pose. The user's effort (H4) between drawing strokes on the mesh or on the canvas was evaluated not only through an usability questionnaire, but also by analyzing the user activities: number of clicks, number of curves created, modified and deleted.

The *independent variables* involved in this experiment were:

- The interaction model (2D sketch-based, 3D sketch-based or traditional).
- The facial expression to be created (see the three poses in Figure 4.3).

The *dependent variables* were:

- The user's effort (easiness).
- The time to create a facial expression.

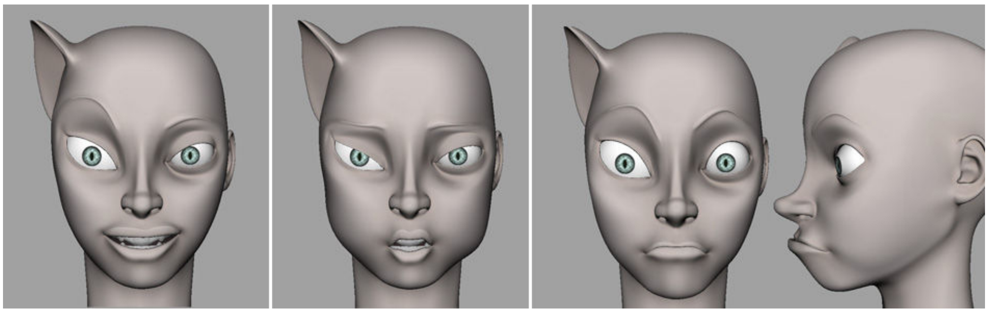


Figure 4.3: The participants in the experiment were asked to recreate these facial expressions using the respective interaction model: the 2D sketching interface, the 3D sketching interface and the traditional approach; left: Pose 1*; middle:* Pose 2*; right:* Pose 3.

4.2.1 Experiment Design

We have tested and validated the system with groups of different profiles from an animation school [1]:

- A group of 30 expert participants which regularly use 3D animation packages (group of graduate students and professional artists)
- A group of 30 non-expert participants with average 3D animation skills (group of undergraduate students)

The experiment was divided into 12 sessions: 6 sessions for each group. Each session was composed by 3 tests (one test for each interaction model): one test using the 2D sketching interface; another using the 3D sketching interface and the third using the traditional technique, i.e. by directly manipulating the rig. Each session was composed by a group of 5 participants and lasted between 40 and 60 minutes. Each interaction model was tested by each

[1]Digital Animation School of University of Veritas, Costa Rica

group in a random order. We assigned an expert artist to monitor each session to collect usability data by observational methods and to approve the quality of the poses created with the three interaction models.

Each test was composed of two phases:

Training Phase - to introduce the respective interaction model. The participants were only instructed with a brief explanation (3 minutes) of what they have to do, i.e. recreate facial expressions. After that, they had 2 minutes to test the respective interaction model.

Task Phase - we gave the participants three examples of facial expressions (Figure 4.3) and asked them to recreate each expression using the respective interaction model, starting from a neutral expression. There was no time limit to conclude the tasks and the only rule was that the user needed to create the facial expressions with the respective interaction model. In the 2D sketch-based interaction model the user only needs to create two facial expressions: *Pose 1* and *Pose 2*. The facial expression in *Pose 3* is not possible to draw with this interaction model because this mode is limited to a 2D fixed plan. Therefore, is not feasible to apply deformations that comes out the mesh, like the bulges of the nose and mouth. The facial expression in *Pose 3*, is only possible to draw using the 3D sketch-based and the traditional interaction model.

After completing the tests for the three interaction models and before any debriefing or discussion took place, we asked the participants to fill in a questionnaire (`http://www.portointeractivecenter.org/sketch/validation`). Lastly, we discussed the three approaches with the participants and asked them to write additional comments at the end of the questionnaire.

4.2.2 Experiment Results

We have carried out two different tests to evaluate the performance of our sketching system and to answer the formulated hypothesis. An *Usability Test* to evaluate the user's effort and a *Time Test* to compute the time that the users took to create a pose. The Shapiro-Wilk test [Shapiro and Wilk 1965] was used to assess the normality of the observed data. The results show that our data was normally distributed.

Usability Test

In order to answer the hypothesis H1 we have analyzed the question Q2 of the usability questionnaire:

- *Which method (sketch-based or traditional) is easier and more intuitive to use?*

We observed that the answers vary with the participant's profile, so the results were very different for experts and non-experts participants (see Figure 4.4).

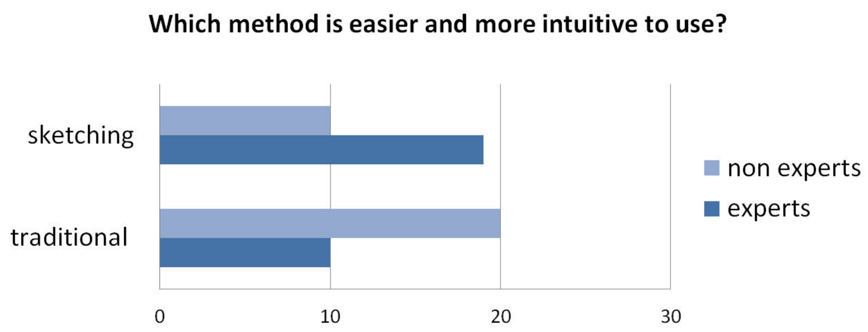


Figure 4.4: Only the expert participants found the sketching method easier and more intuitive to use.

With a 95% confidence interval for the mean ($M = 0.66, SD = 0.48, CL_{.95} = 0.50\ to\ 0.80$), we can affirm that the expert participants agree that the sketching method is easier and more intuitive to use than the traditional technique.

On the contrary and with the same confidence interval for the mean ($M = 0.33, SD = 0.47, CL_{.95} = 0.18\ to\ 0.48$), we can state that the non-expert participants disagree that the sketching method is easier and more intuitive to use than the traditional technique.

During the 3D sketching tests, we observed that the non-experts could not easily predict the relationship between the drawn stroke and the final result. For this reason, they answered that they prefer the traditional method where they can, step-by-step, achieve their desired result. On the other hand, we observed that experts knew in advance how the stroke should be drawn and what would be the final deformation.

Therefore, our hypothesis H1 was accepted by expert users and rejected by non expert users.

In order to answer the hypothesis H4 to know the user's effort between drawing strokes on the 3D mesh and on the 2D canvas, we analyzed the user's activities.

The results were very similar between experts and non-experts participants. In both cases it is suggested that the 2D interface demands less user's effort. In fact, it requires fewer clicks to create the same facial pose: The system logged about 2x fewer clicks when compared with the 3D sketching interface (see Figure 4.5 left).

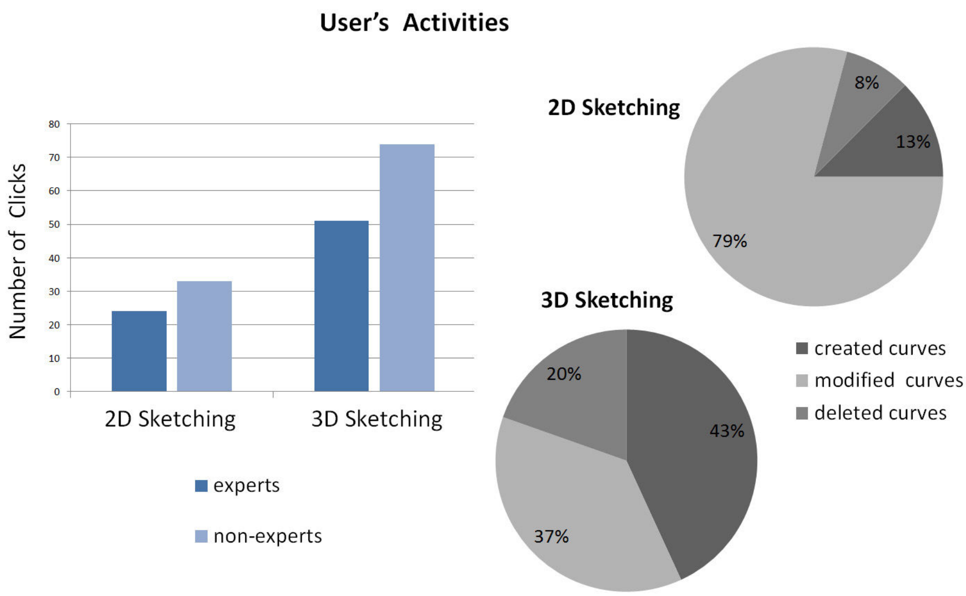


Figure 4.5: User's activities during the sketching tests for experts and non-experts users. left: Number of clicks; right: Number of curves created, modified and deleted.

During the 2D sketching tests, we observed that the users prefer to modify the curves control points than create new strokes. In fact, the system logged that about 79% of the clicks were used to edit existents curves. On the other hand, in the 3D sketching tests, the user draws strokes repeatedly on the 3D mesh (about 43% of the clicks were used to create new strokes). When the deformation is close enough to the desired result the user stops sketching and edits the curve control points to refine the deformation (approximately

37% of the clicks were used to change existent curves). In the 3D sketching tests, much more curves were deleted when compared with the 2D sketching interface. In fact, during the 3D tests, about 20% of the clicks were used to delete curves.

Also the questionnaire results confirmed our observations. Actually, after analyzing the results of question Q9:

- *Which do you think is more intuitive: sketching on the canvas or on the mesh?*

The results were very similar for experts and non-experts participants (see Figure 4.6).

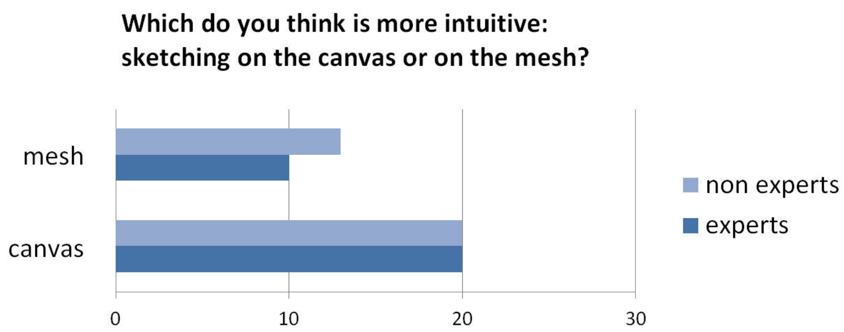


Figure 4.6: All the participants, experts and non-experts, found sketching on the canvas more intuitive than on the 3D mesh.

We can state with a 95% confidence interval for the mean ($M = 0.67, SD = 0.47, CL_{.95} = 0.52$ *to* 0.82), that the participants agree that it is easier and more intuitive to draw strokes on the canvas than doing it directly on the 3D mesh.

Therefore, we accept the hypothesis H4 by both expert and non-expert users.

The results of this usability test revealed quite curious, when compared to a previous pilot study [Miranda et al. 2012] between the 2D and 3D sketching interfaces. Our pilot study showed that the 3D interface was faster and demands less user's effort than the 2D one, but recent testing proves the contrary. While on our previous pilot study the participant had a guide that explained the regions of the face, in this study the participants did not have any help. So, we observed in the 3D sketching interface that the users could not easily identify the region to be deformed and, consequently, many clicks were done and curves were modified and deleted. Therefore, we concluded that the interaction mode between the action of the user and the deformation of the model must include a visual feedback with the facial regions to assist the user. A solution could be to simply highlight the region to be deformed, allowing the user to correctly identify the desired area. This will be subject for a future reimplementation of the plugin.

Time Test

In order to answer the hypothesis H2 and H3, we analyzed the average time to create a pose for each interaction model (see Figure 4.7).

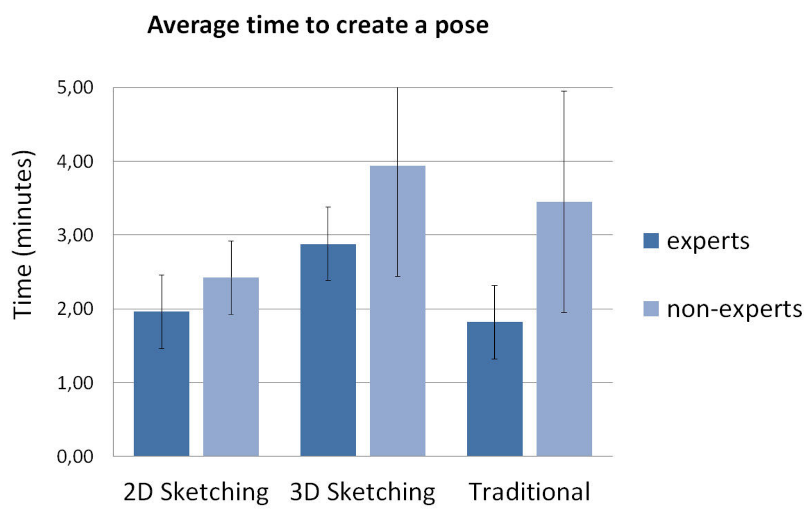


Figure 4.7: We recorded the time it takes the participants to create each expression with each interaction mode. This graph shows the timing results for experts and non-experts users.

To evaluate if the interaction model has a significant effect on the time to create a pose, we accomplished statistical tests. We performed a one-way repeated measure ANOVA [2] on the time to create a pose with the three inter-

[2]Based on [Field and Hole 2003], analysis of variance (ANOVA) is a parametric test used when there are three or more levels of the independent variable. When the same participants take part in all experimental conditions, a one-way repeated measure ANOVA is employed.

action methods. Post-hoc analysis was performed using Fisher's LSD comparisons of means [Fisher 1925], which is a conservative test for significance.

The results vary accordingly to the participant profile, as explained in the following.

Expert Users. The results of this study revealed that the 2D sketching interface was practically as fast as the traditional technique. The participants took an average of 1.96 minutes to create a pose with the 2D sketching interface and an average of 1.82 minutes with the traditional technique. With the 3D sketching interface they took an average of 2.88 minutes. We see this as a very positive result because these kind of participants have years of training using the individual controls of the rig in Maya.

The data were analyzed using a one-way repeated measure ANOVA. The results showed that the interaction model had a significant effect on time $F(2,29) = 39.764, p = 0.000$. Performing pairwise comparisons using Fisher's LSD test revealed that the 2D sketching interface was significantly different from 3D interface ($p = 0.000$) but not significantly different from the traditional technique ($p = 0.285$). Therefore, we cannot affirm that the 2D Sketching interface reduces the user's time to create facial expressions when compared to the traditional technique. *Consequently the hypothesis H2 can neither be accepted nor rejected for expert users.*

The test also revealed that the 3D sketching interface was significantly different from the traditional technique ($p = 0.000$). In fact, the user's time to create facial expressions using the traditional technique was faster than the 3D sketching model. *Therefore, we reject the hypothesis H3 for expert users.*

Non-Expert Users. The results of this study reveal that the 2D sketching interface was faster for creating facial expressions when compared to the other two approaches. The participants took an average of 2.43 minutes to create a pose with the 2D sketching interface, an average of 3.94 minutes using the 3D sketching interface and an average of 3.45 minutes with the traditional technique.

The data were analyzed using a one-way repeated measure ANOVA. The results showed that the interaction model had a significant effect on time $F(2,29) = 9.693, p = 0.000$. Performing pairwise comparisons using Fisher's

LSD test revealed that the 2D sketching interface was significantly different from 3D sketching interface ($p = 0.000$) and from traditional technique ($p = 0.005$). Therefore, we can affirm that the 2D Sketching interface is faster creating facial expressions when compared to the 3D sketching mode and the traditional approach. *Consequently, the hypothesis H2 is accepted for non-expert users.*

The test also revealed that the 3D sketching model was not significantly different from the traditional approach ($p = 0.182$). *Therefore, the hypothesis H3 can neither be accepted nor rejected for non-expert users.* We cannot affirm that the 3D Sketching interface reduces the user's time to create facial expressions when compared to the traditional technique.

Figure 4.8 shows the difference time to create a pose, between expert and non-experts participants, for each interaction model. The time results showed that the expert participants were about 2x faster than the non-expert participants to create a pose with the traditional approach. This difference between experts and non-experts is less significant when they use the sketching paradigm. In fact, this value fell to about 27% when the 3D sketching is used and to about 19% when they used the 2D sketching interface. Therefore, the 2D sketching interface seems to require a shorter learning curve.

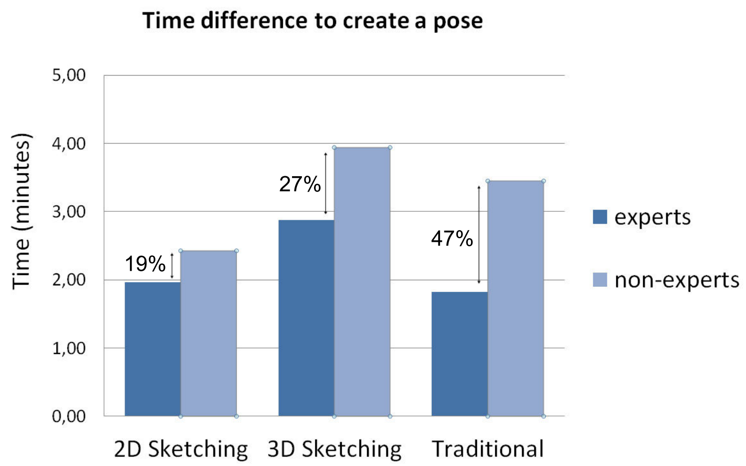


Figure 4.8: The time difference between experts and non-experts, to create a pose, is less significant when they use the sketching approach.

The summary of the user's qualitative comments about the sketching system are:

- Both interaction models in the sketching method are simple and useful for creating facial deformations;
- Both interaction models in the sketching method produce fast results, mainly in regions that have many joints;
- The 2D sketching method allows fast and very precise curve editing;
- The 2D sketching interface is better to achieve accurate details, compared to the 3D sketching interaction model;
- The 3D sketching interface is better for a fast approximation to the pose, compared to the 2D sketching interaction model.
- The 3D sketching interface is better for users with drawing experience than users with only 3D modeling and animation skills.

4.3 Facial Retargeting Experiment

The perception of a facial expression can potentially be affected by many elements. The mesh geometry, mesh details (subtleties), the character style (realistic, cartoon, fantastic) can have an impact on both the final results of the facial expression and how they are perceived by the spectator. Therefore, we included in this experiment different character styles, each one with different details and geometry of different resolutions.

We want to evaluate if our retargeting method preserves, in the target models, the original emotion manually created on the source character by an artist, using our sketching system. Therefore, we have formulated the following hypotheses for this experiment:

- H1: The facial expression automatically transferred from a source model to a target model keeps the same emotion;

The *independent variable* involved in this experiment was the face of the 3D characters presented in figure 4.1. The *dependent variable* was the emotion transmitted in the facial expression of the characters.

4.3.1 Experiment Design

Thirty participants, 15 males and 15 females, aged between 25 and 45, completed the test. All of them were unfamiliar with the experiment and had no formal knowledge of 3D animation. All of them self-reported normal or corrected-to-normal vision.

We have designed a test based on matching tasks. We put on a table the four source models of the Figure 3.22 and gave the participants 20 cards. Each card has a printing of the target facial models presented in the Figure 3.22. We asked the participants to match the facial emotion of the target models with the facial emotion of the source model. There was no time limit to conclude the task and the only rule was the participant need to associate each card with the respective source model. Figure 4.9 shows a participant performing the test.

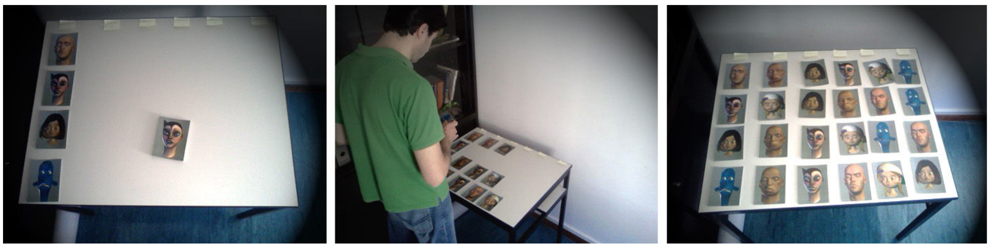


Figure 4.9: A participant realizing the retargeting experiment.

After completing the test, we asked the participants to answer one simple question:

1. Which character's emotion was the most difficult to understand?

4.3.2 Experiment Results

We have carried out a test to evaluate the precision of the retargeting method and to answer the formulated hypothesis. The observed data in this experiment follows a normal distribution, accordingly with the Shapiro-Wilk test.

Precision Test

Figure 4.10 shows the average precision of our retargeting method, by character.

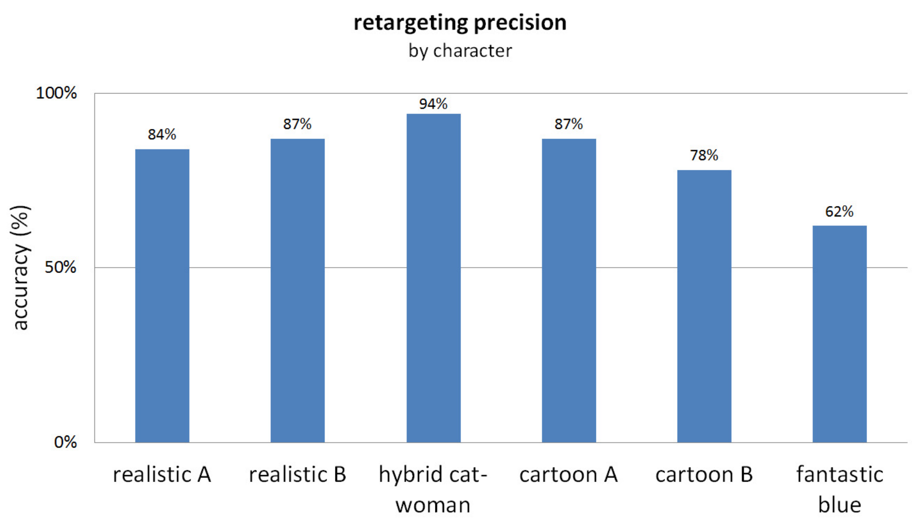


Figure 4.10: The blue character was the one most difficult to perceive his emotion during the Retargeting experiment.

The results of this study reveals that our retargeting method has, globally, 82% of accuracy. We can state, with a 95% confidence interval for the mean ($M = 0.82, SD = 0.26, CL_{.95} = 0.74 \; to \; 0.90$), that the facial expression transferred from a source model to a target model keeps the same emotion. *Therefore, we accept the hypothesis H1.*

In order to identify the character's emotion most difficult to understand, we performed a one-way repeated measure ANOVA on the emotion's perception for the six characters. The results show that the facial character had a significant effect on the emotion's perception $F(5,29) = 6.283, p = 0.000$. Performing pairwise comparisons using Fisher's LSD test revealed that the fantastic-style character, which we call *blue*, was significantly different from all the other characters ($p < 0.005$). The other characters do not show significant differences among them ($p > 0.005$).

The questionnaire results confirmed our statistic test (see Figure 4.11).

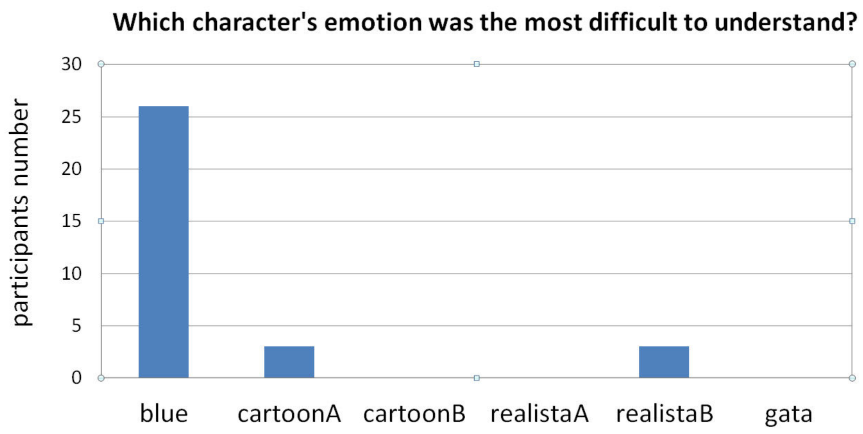
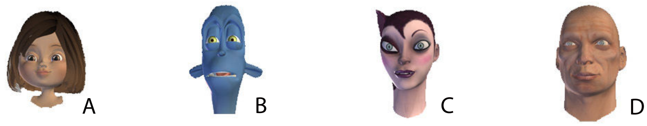


Figure 4.11: Twenty six participants agree that the emotion of the blue *character is the most difficult to be perceived.*

After analyzing the results of the question Q1, we can affirm, with a 95% confidence interval for the mean ($M = 0.87, SD = 0.34, CL_{.95} = 0.76\, to\, 0.97$), that the participants agree that the *blue* character emotion is the most difficult to be perceived. We found two reasons for that result. First, the *blue* model has low resolution in the mouth region which makes the perception of micro-expressions difficult in that region. Second, the *blue* character is the one that diverts the farthest from a real character. This means that it is easier to recognize an emotion in a realistic face than in a non-realistic face. That is why the facial animation for realistic faces is so complex, because the minimum imperfection is easily identified due to the spectators' familiarity to human faces.

4.4 Performance Test

Our system allows creating facial poses in real time. The user is able to sculpt and edit the model by drawing strokes interactively and see the changes instantaneously. In order to evaluate the response time of the system we used four models with a different number of triangles (see Table 4.1). Results show how the system works in real time with up to 50.000 triangles; it then suffers from a small delay of about 250 ms. After this delay, the application starts losing its real time interactive response. We have tested the response time on characters with and without textures, and we have not experienced any significant performance change. Only when about 80.000 triangles is attained, we can notice some diminishing performance with textured characters. The tests were made on an Intel Core 2 Duo, with 2GB RAM and an ATI Radeon X1600 graphics card.



Model	Triangles	Time	Triangles	Time	Triangles	Time
A	29.546	90	41.100	110	82.676	320
B	4.593	80	14.386	80	53.348	250
C	12.284	80	45.536	180	178.544	900
D	16.286	80	24.924	80	59.472	250

Table 4.1: System response times (in milliseconds).

4.5 Case Study for Therapeutic Purposes: LIFEisGAME

We illustrate the versatility of our sketching method with a learning tool for therapeutic purposes. LIFEisGAME (LearnIng Facial Emotions usIng Serious GAMEs, `http://www.portointeractivecenter.org/lifeisgame`) attempts to apply a serious game approach to teach children with ASD to recognize facial emotions using real-time automatic facial expression analysis and virtual character synthesis. Based on the learning cycle defined in [Kolb 1984], we have outlined in LIFEisGAME four different pedagogical modes. These range from static to interactive facial emotion recognition.

The sketching method presented on this thesis has been adapted in one of the game modes that we call *"'Build a Face"'*. It runs on regular and touch-screen computers. The game starts with the player choosing a character from a list of 3D models and the game mode he wants to play. All modes share the same user interaction model: the *2D sketching interface*. Figure 4.12 shows the user interface in which the player controls the expressions of the 3D character by drawing strokes on a canvas on the right-side of the screen. The player can drag facial poses to the timeline on the bottom of the screen and, after setting different expressions, he/she can play the animation. The player can also take a picture of himself performing a facial expression and then reproduce the expression by sketching it on the interface. For more information on the LIFEisGAME project we recommend the reading of [Abirached et al. 2011; Fernandes et al. 2011].

Figure 4.12: LIFEisGAME, sketch-based interface of the game mode Build a Face. *right: the player can draw strokes on the 2D canvas and automatically deform the cartoon face model; bottom: timeline to drag and drop the facial poses.*

We carried out a pilot study of five children with varied ASD diagnoses. The testing sessions took place at CRIAR (Autism Association in Portugal) and every child was accompanied by at least one therapist. In the session, participants were asked to play with the two versions of the *Build a Face* game mode: free-drawing and mimic your picture. The UI configuration is the 2D sketching interface and the participants only used a touch-screen computer. The testing result suggests that, in general, the children responded favorably to the game and enjoyed animating 3D avatars due to the simplicity of the interaction model. We verified also that some children wanted to draw directly on the 3D model instead of using the 2D canvas. Therefore, we intend to prepare a new experiment to study and analyze which user interface (2D or 3D sketching) is the most adequate for children with ASD.

Chapter 5

Conclusions and Future Work

This thesis describes a new approach to manipulate a rig, based on a free-form sketch-based control method. The sketching method is used to create a real time control system where facial deformation is sketched on. Based on its modular design, the facial sketching control system developed in this research can be easily integrated into existing animation production pipelines and significantly improve the production workflow. This chapter summarizes the main conclusions extracted from our research and defines some guidelines to future work.

5.1 Conclusion

Reproducing the subtleties of a face through animation requires a sophisticated character rig and an associated user interface to provide high-level controls to ease the rig manipulation. As the complexity of the rig grows, creating all the facial poses of each character is a slow and manual process. We present a generic facial sketching control system that allows *easy*, *rapid* and *interactive* prototyping of facial poses. Our approach acts directly on the rig of the model, hiding its complexity from the user, who only needs to draw strokes. The strokes can be drawn directly on the 3D facial mesh or on a virtual canvas.

The method developed in this thesis is independent of the underlying rig structure and works with any character style, from realistic to cartoon and fantastic characters. The 3D models can be defined as a polygonal mesh or a NURBS surface and there is no limit to the number of vertices. However, in the tests performed, we observed that with more than 50.000 triangles the system starts losing its interactive response in real time. The 3D quality of the models follows the entertainment industry requirements, which was fundamental to justify that the results are suitable for high quality CG productions.

In films and videogame productions, artists often build one base model and then modify it to create new facial poses. Currently, the artists would need to fine tune the model by directly modifying the geometry or editing several controls of the rig to reflect the new face. We propose a change of paradigm in the way a rig can be manipulated. Traditional techniques require the manipulation of its controls individually, in a discontinuous way, which can be very time expensive. Our sketching method allows to manipulate a large number of rig elements at the same time, through a single control curve drawn on the user interface. As several rig elements are encapsulated in just one control curve, it is possible to rapidly create complex deformations with just a single and continuous movement of the hand.

We have developed two different sketching interaction modes: *2D Sketching Interface* and *3D Sketching Interface*. In both modes, the user draws free-form 2D strokes and the system automatically infers depth information, by constraining the rig elements to the 3D mesh. To allow deformations not constrained by the 3D mesh we introduced a 2.5D billboard canvas. It allows the user to create bulges on the 3D mesh, in any direction. Combining the direct manipulation on the 3D mesh and the 2.5D billboard canvas permits to go around the limitations associated to the 2D sketching interface, which is view-dependent and does not grant non-tangent deformations in the 3D face.

Our sketching method works on the top of a rig structure. This reduces the ambiguity problem, which occurs in most of the other sketching systems, since all deformations made by strokes are always constrained by the underlying rig. This allows the user to freely and easily draw, without any special previous experience and knowledge on the system. However, this does not mean that all strokes will always produce the correct deformation on the mesh, but, at least, they will be made accordingly to the defined rig. In contrast to the majority of the sketching systems, which are low in precision, the geometric precision of the deformation made by a stroke, in our approach, is always constrained by the rig.

During a production, animators often ask for new rig elements to perform new deformations, like subtle movements of the corner of the lips, which were not contemplated on the original rig design. In order to support the new demands, the rig elements as well as the user interface control system must be updated. With our sketching approach, the user interface always keeps the same, even with the adjustments of the underlying rig. However, the regions must be redefined again so that the system becomes ready to use.

The facial sketching system was tested and evaluated on realistic, cartoon and fantastic characters, to show the versatility of the system. Throughout our experiments, we have evaluated the usefulness of our sketching system. We tested its usability by measuring the user's effort and its performance by computing the time the user took to create a pose. The timing results of our sketching interaction models show some variations depending on the expertise level of the participants. Our *2D sketching interface* revealed to be as fast as the traditional approach with expert users, but faster with non-experts. The *3D interface* was a little slower than the traditional technique among the expert users, but does not presents significant time differences with non-experts. We consider these results positive, since the persons involved in the tests have years of training in Maya and were completely unfamiliar to our sketching interaction models. We presented the results to Technical and Art Directors, who approved the quality of the poses and animations to be used in CG productions, replacing the artist generated ones. This is a crucial result: if the output still requires a lot of tunning, then the sketching system is useless in a production.

The experiments performed allowed to extract the following conclusions:

- the sketching interaction model is simple to master and useful to create facial deformations, producing fast results. The participants were able to create facial poses in a very short amount of time (between 2 and 4 minutes), without any training period, leveraging the intuitive sketching process, similar to hand-drawing;
- The sketching interaction paradigm requires a shorter learning curve when compared to traditional rigging techniques;

- The 2D sketching interface is better for users without experience in moving around the 3D space, when compared to the 3D sketching interface;

Although sketching usually is more natural and intuitive to draw facial expressions, the rig direct manipulation can be more accurate because it allows to edit the rig's controls one by one. So, the artist might prefer it in certain cases. However, the facial sketching control system developed provides both interaction modes. It allows to draw free-form strokes to perform a rapid approximation to the desired deformation and then to edit, individually, the curve points, to achieve precision. Another advantage when compared to traditional rigging techniques is that, with our system, the user does not need to understand how to use the rig parameters. On the contrary, he just needs to sketch.

Another important feature of the system here proposed is the retargeting of facial poses between different characters. The retargeting method was tested to evaluate its accuracy. The results of the tests show that the method has 82% of precision. In practice, it means that our retargeting method preserves the original emotion created by the artist manually in the source model in the target models. We consider this result positive because the correspondent poses were transferred instantly. In order to refine some facial deformation on the target character, the user can easily edit the transferred strokes. The system is able to speed up a CG production, because the artist does not need to create the same facial expression in all the characters. Instead, the artist can create facial expressions just to one character and then reuse the created poses in other characters. This improves the workflow as it speeds up the creation of facial poses, which means increased productivity and reduced costs. However, the developed retargeting method requires that all the characters, source and target, have the same rig structure, which turns out to be a limitation.

Although the focus of this thesis is on the dynamics of facial sketching for artists, the system developed has been further explored in applications with learning purposes [Abirached et al. 2011; Fernandes et al. 2011], which benefits from the core method developed in this research.

Please, refer to `http://www.portointeractivecenter.org/sketch` to view the videos and additional material related to this research.

So, the answer to the hypothesis that inspire this research is:
yes, it is possible to simplify the rig control process, to generate complex deformations on any 3D face, in real time and through a continuous sketching interaction.

5.2 Future Work

We conclude this thesis by suggesting some potential directions for future work. Following this research, an interesting new approach could be the extension of the method to control other type of objects that are not a face. Figure 5.1 shows the first results we have achieved in controling a hand and a rope.

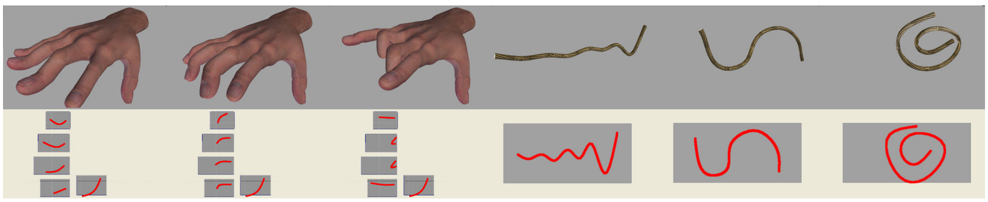


Figure 5.1: Method generalization; left: The hand model has 19 joints, which are controlled by five 2D fixed and predefined canvas, one for each finger; right: The rope model has 9 joints, which are controlled just by one 2.5D dynamic and billboard canvas.

There are many interesting research guidelines that can benefit from the developed method and extend the implemented *facial sketching system*.

- **Human Computer Interaction:** A possible future development is to combine our sketching interaction model with other traditional rigging techniques. An interesting case is to use the sketching paradigm to directly manipulate blendshapes. Lewis and Anjyo approach has already taken some steps in this direction [Lewis and Anjyo 2010]. Their technique to directly manipulate blendshapes is simple and efficient but the interaction model continues to be traditional, based on the individual selection of control points. Their *discontinuous* interaction could be improved by our sketching method, which will allow the manipulation, in a *continuous* way, of a large number of blendshapes, at the same time, with a single stroke. Another interesting direction can be to use the sketching method to directly control the skin. By drawing a stroke on a certain region of the mesh, the method could increase, on the fly, the number of polygons in that region (tesselation), in order to emphasize some facial features, like wrinkles.

- **Facial Analysis and Recognition:** A facial model can have different shapes and visual styles, and is divided in several regions. A motivating research direction is the automatic mapping of these regions: based on the model's morphology, the system would suggest the regions definition and would create the respective drawing areas automatically. While in an anatomically correct face it is not hard to infer the facial regions (2 brows, 2 eyes, 1 nose, 2 cheeks, 1 mouth), the same is very challenging to a non-anatomic face.

- **Emotion's Perception:** An interesting research guideline is related to the perception of emotions. It will be interesting to study if it is better for the artist, while he is deforming a face, to understand emotions through sketching interfaces in contrast with traditional interfaces. *It will be better for the artist to perceive the emotion through a continuous or discontinuous interaction?*

- **Retargeting:** The actual version of the system allows the retargeting of facial poses between characters that have the same rig. It will be interesting to extend the method to support transferring strokes to models with different rig structures.

The method developed in this research can become part of different types of applications, like educational learning tools, fast modeling prototyping and game interface. It can also be integrated in a variety of devices like digital tables, mobile phones and iPads.

Facial Rigging and Animation, as well as Sketching Interaction, are hot topics that will continue to provide many research challenges in the next years. Much work remains to be done and we are excited about the possibilities that lie ahead. We hope our approach and work motivates other researchers to come up with new ideas on these areas.

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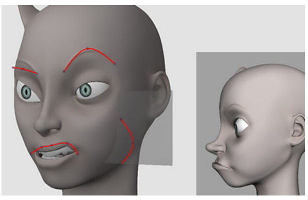
Appendix A

Publications and Awards

A.1 Publications and Conferences

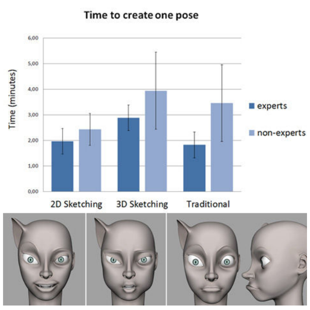
These are the most significant publications and respective abstracts that resulted from the PhD research.

[2012]



MIRANDA, J. C., ALVAREZ, X., ORVALHO, J., GUTIERREZ, D., SOUSA, A. A., AND ORVALHO, V. 2012. Sketch express: A sketching interface for facial animation. In *Journal Computer and Graphics*, Issue 6, Volume 36, Pp. 585-595. *Prémio Professor José Luis Encarnação 2012 - Honorable Mention.*

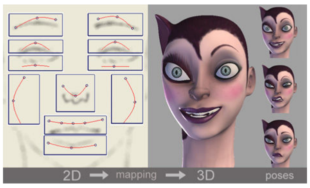
One of the most challenging tasks for an animator is to quickly create convincing facial expressions. Finding an effective control interface to manipulate facial geometry has traditionally required experienced users (usually technical directors), who create and place the necessary animation controls. Here we present our sketching interface control system , designed to reduce the time and effort necessary to create facial animations. Inspired in the way artists draw, where simple strokes define the shape of an object, our approach allows the user to sketch such strokes either directly on the 3D mesh or on two different types of canvas: a 2D fixed canvas or more flexible 2.5D dynamic screen-aligned billboards. In all cases, the strokes do not control the geometry of the face, but the underlying animation rig instead, allowing direct manipulation of the rig elements. Additionally, we show how the strokes can be easily reused in different characters, allowing retargeting of poses on several models. We illustrate our interactive approach using varied facial models of different styles showing that first time users typically create appealing 3D poses and animations in just a few minutes. We also present in this article the results of a user study. We deploy our method in an application for an artistic purpose. Our system has also been used in a pioneer serious game context, where the goal was to teach people with Autism Spectrum Disorders (ASD) to recognize facial emotions, using real time synthesis and automatic facial expression analysis.



MIRANDA, J. C., ALVAREZ, X., SOLENO, J., SOUSA, A. A., FERNÁNDEZ, I., AND ORVALHO, V. 2012. Perceiving Interactive Sketching Through Facial Expressions. In *Proceedings of the ACM Symposium on Applied Perception (SAP '12)* . ACM, New York, NY, USA, Pp. 127. *Best Poster/Demo* :: Selected for SIGGRAPH'12 Poster Session.

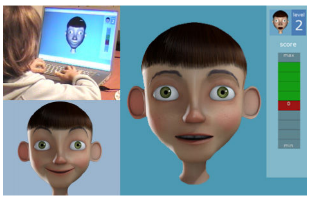
The videogame and film industry drive the demand for powerful intuitive interfaces that allow artists to quickly produce believable facial expressions. For an effective interface to create facial deformation, we have developed a facial sketching interface control system, based on simple strokes drawn directly on a 3D face or on a 2D virtual canvas. We present a user study to understand which interaction models ease the creation of facial expressions. We tested and validated the system in order to compare our different sketching interaction models and the traditional rigging technique. The results show that users are able to create facial poses in a very short amount of time with our sketching interaction models, even without any previous training. This allows to control a 3D model in an intuitive sketching process, just like simply painting with a brush on a canvas. The sketching interaction paradigm requires a shorter learning curve when compared to the traditional technique. The 2D mode reveals more user-friendly for people that have low expertise and the 3D for those with drawing experience.

[2011]



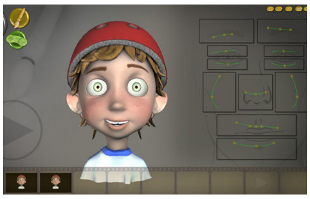
MIRANDA, J. C., ALVAREZ, X., ORVALHO, J., GUTIERREZ, D., SOUSA, A. A., AND ORVALHO, V. 2011. Sketch express: facial expressions made easy. In *Proceedings of the Eighth Eurographics Symposium on Sketch-Based Interfaces and Modeling (SBIM '11)*. ACM, New York, NY, USA, 87-94. *Best Paper Award.*

Finding an effective control interface to manipulate complex geometric objects has traditionally relied on experienced users to place the animation controls. This process, whether for key framed or for motion captured animation, takes a lot of time and effort. We introduce a novel sketching interface control system inspired in the way artists draw, in which a stroke defines the shape of an object and reflects the user's intention. We also introduce the canvas, a 2D drawing region where the users can make their strokes, which determines the domain of interaction with the object. We show that the combination of strokes and canvases provides a new way to manipulate the shape of an implicit volume in space. And most importantly, it is independent from the 3D model rig. The strokes can be easily stored and reused in other characters, allowing retargeting of poses. Our interactive approach is illustrated using facial models of different styles. As a result, we allow rapid manipulation of 3D faces on the fly in a very intuitive and interactive way. Our informal study showed that first time users typically master the system within seconds, creating appealing 3D poses and animations in just a few minutes.



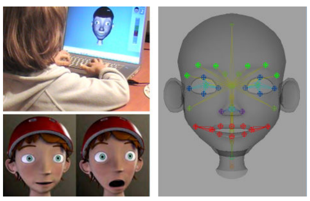
MIRANDA, J. C., FERNANDES, T., SOUSA, A. A., AND ORVALHO, V. 2011. Interactive Technology: Teaching People with Autism to Recognize Facial Emotions. In *Book chapter Autism Spectrum Disorders - From Genes to Environment*. Tim Williams (Ed.), ISBN: 978-953-307-558-7, InTech.

In daily life, we interact with others by exchanging a huge quantity of information, including our current states of emotions, through facial expressions. Thus, faces are crucial for the recognition and understanding of emotions and for assisting communications and interactions between people. Individuals with Autism Spectrum Disorders (ASD) tend to avoid looking at others human faces and find it hard to recognize facial expressions and emotions in themselves and in others (Baron Cohen, 1995). This incapacity to read emotions on the human face impairs their ability to communicate with other people (Baron-Cohen et al., 2007). This article gives an overview of existing methods that have been used for teaching emotion recognition to individuals with ASD. We identify some technological limitations that difficult their interpersonal interactions. Our contribution is a novel approach to teach autistic people to recognize emotions from facial expression. Our idea is based on real-time facial synthesis of 3D characters. We also suggest a different interaction model to involve the autistic patient more deeply in the process of learning emotions. Creating a solution to solve this problem requires a joint effort from many research fields, such as computer vision, computer graphics, human computer interaction and facial behavior and emotions.



Fernandes, T., Alves, S., Miranda, J., Queirós, C., Orvalho, V. 2011. A facial Character Animation System to Help Recognize Facial Emotions. In *HCist International Workshop on Health*. Springer.

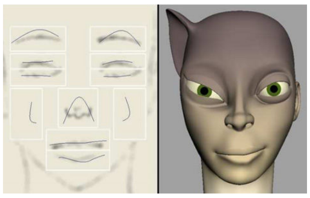
This article presents the LIFEisGAME project, a serious game that will help children with ASD to recognize and express emotions through facial expressions. The game design tackles one of the main experiential learning cycle of emotion recognition: recognize and mimic (game mode: build a face). We describe the technology behind the game, which focus on a character animation pipeline and a sketching algorithm. We detailed the facial expression analyzer that is used to calculate the score in the game. We also present a study that analyzes what type of characters children prefer when playing a game. Last, we present a pilot study we have performed with kids with ASD.



B. Abirached, J. K. Aggarwal, T. Fernandes, J. Miranda, V. Orvalho, B. Tamersoy, Y. Zhang 2011. Improving Communication Skills of Children with ASDs through Interaction with Virtual Characters. In *IEEE International Conference on Serious Games and Application for Health (SeGAH'11)*. Braga, Portugal.

This article presents the LIFEisGAME project, a serious game that will help children with ASDs to recognize and express emotions through facial expressions. The game design tackles the main experiential learning cycle of emotion recognition: watch and recognize, learn by doing, recognize and mimic, generalize or knowledge transfer to real life. We briefly describe the technology behind the character animation pipeline centered on the creation of a generic rig. Then, we detail the facial expression analyzer that uses Active Appearance Models. Last, we describe the user study experiment using game mode "‘recognize the expression"’.

[2010]



MIRANDA, J. C., ALVAREZ, X., SOUSA, A. A., GUTIERREZ, D., ORVALHO, J., AND ORVALHO, V. 2010. Painting on Canvas: A Facial Sketching Control System. In *Eurographics/ACM SIGGRAPH Symposium on Computer Animation (SCA 2010) (Poster and Demo)*. ACM, Madrid, Spain, Vol. 1, pp. 1 - 2, July, 2010.

Facial Animation in films and videogames has traditionally relied on creating all the facial poses and animation controls in the early stages of a production. This process, whether for key framed controls or motion captured animation, takes a lot of time and effort. We present a novel sketching control system inspired in the way artists draw, where a stroke defines the shape of an object and reflects the userŠs intention. We introduce the canvas, a 2D drawing region where the users can make their strokes. We present a Sketch-Based Free-Form Deformation technique that is used to create a real-time simple control system where facial deformation is sketched on, significantly speeding up the creation of poses. We show that the combination of strokes and canvases provides a new way to manipulate the shape of an implicit volume in space. As a result, we allow rapid prototyping of facial expressions on the fly in a very intuitive and interactive way. Our informal study showed that first time users typically master the system within seconds, creating appealing 3D facial poses and animations in just a few minutes.

ORVALHO, V., MIRANDA, J. C., AND SOUSA, A. A. 2010. What a Feeling: Learning Facial Expressions and Emotions. In *Revista Prisma, Edição nž 10 - Especial videojogos 2010. Best paper in Conferência de Ciências e Artes dos Videojogos 2009. Universidade de Aveiro, Portugal.*

People with Autism Spectrum Disorders (ASD) find it difficult to understand facial expressions. We present a new approach that targets one of the core symptomatic deficits in ASD: the ability to recognize the feeling states of others. *What a Feeling* is a videogame that aims to improve the ability of socially and emotionally impaired individuals to recognize and respond to emotions conveyed by the face in a playful way. It enables people from all ages to interact with 3D avatars and learn facial expressions through a set of exercises. The game engine is based on real-time facial synthesis. This paper describes the core mechanics of our learning methodology and discusses future evaluation directions.

[2009]

ORVALHO, V., MIRANDA, J. C., AND SOUSA, A. A. 2009. Facial Synthesis of 3D Avatars for Therapeutic Applications. In *Journal of Studies in Health Technology and Informatics*. IOS Press. 144:96-98. ISSN: 0926-9630.

People with autism spectrum disorder (ASD) find it difficult to recognize and respond to emotions conveyed by the face. Most existing methodologies to teach people with ASD to recognize expressions use still images, and do not take into account that facial expressions have movement. We propose a new approach that uses state of the art technology to solve the problem and to improve interactivity. It is based on an avatar-user interaction model with real time response, which builds upon the patient-therapist relationship: it is designed to be used by the therapist and the patient. The core technology behind it is based on a technique we have developed for real time facial synthesis of 3D characters.

Orvalho, V., Miranda, J. C., and Sousa, A. A. 2009. What a Feeling: Learning Facial Expressions and Emotions. In *Proceedings of Videojogos 2009 - Conferência de Ciências e Artes dos Videojogos*. Universidade de Aveiro, Portugal.

People with Autism Spectrum Disorders (ASD) find it difficult to understand facial expressions. We present a new approach that targets one of the core symptomatic deficits in ASD: the ability to recognize the feeling states of others. *What a Feeling* is a videogame that aims to improve the ability of socially and emotionally impaired individuals to recognize and respond to emotions conveyed by the face in a playful way. It enables people from all ages to interact with 3D avatars and learn facial expressions through a set of exercises. The game engine is based on real-time facial synthesis. This paper describes the core mechanics of our learning methodology and discusses future evaluation directions.

A.2 Invited Talks

Sketch Express: Facial Expressions Made Easy. Semana da Ciência e Tecnologia. Instituto Politécnico da Guarda (IPG). Guarda, Portugal. Novembro 2011.

T-Life - um programa de treino da capacidade de reconhecimento emocional em pessoas com perturbações do espectro autista. I Congresso Internacional da Saúde. Simpósio: Realidade Virtual aplicada ao contexto da Saúde e Reabilitação. Gaia, Porto, Portugal. Setembro 2010.

Animação Facial 3D no domínio da Reabilitação. Seminário de Engenharia Informática: Às cegas com ... Engenharia. Instituto Politécnico da Guarda (IPG). Guarda, Portugal. Abril 2010.

T-Life - um projecto de reconhecimento emocional de faces em pessoas com autismo. VI Congresso Nacional de Terapia Ocupacional. WorkShop: As Novas Tecnologias Aplicadas ao Contexto da Saúde e Reabilitação - Algumas Aplicações de Metodologias de Realidade Virtual. Alcochete, Lisboa, Portugal. Abril 2010.

A.3 Honors and Awards

Best Paper Award Winner. Sketch express: facial expressions made easy. In *Eighth Eurographics Symposium on Sketch-Based Interfaces and Modeling (SBIM '11)*. ACM, Vancouver, Canadá, August 2011.

Best Poster/Demo Award Winner. Perceiving Interactive Sketching Through Facial Expressions. In *ACM Symposium on Applied Perception (SAP '12)*. ACM, Los Angels, USA, August 2012.

Honorable Mention (2nd Place). In *Prémio Professor José Luis Encarnação 2012, promoted by the Portuguese Computer Graphics Group (GPCG)*, with the article *Sketch express: A sketching interface for facial animation*, published in *Journal Computer and Graphics, Issue 6, Volume 36*. GPCG, Viana do Castelo, Portugal, Outubro 2012.