A skeleton/cage hybrid paradigm for digital animation

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Abstract. Digital animators require simple tools and techniques that allow them to create computer animations in an easy, fast and intuitive way. To perform this kind of task, several methods are available, like cage-based or skeleton-based skinning. Cages and skeletons allow animators to define mesh deformation in order to obtain a character pose. Both of them have different pros and cons, and different expressive power. We aim to create a new skinning technique using a skeleton/cage hybrid paradigm that merges together the expressive power of both of them, reducing the complexity of pose definition and making the animation pipeline more simple, intuitive and straightforward.

1 Introduction

Nowadays, computer graphics is widely used by all kinds of industries: cinematographics, videogames, engineering, medical and so on. Computer animation is one of the most important branches of computer graphics, and it makes it possible to give the idea of movement of three-dimensional characters or objects.

Artists and digital animators require powerful tools that allow them to generate computer animations in an easy, fast and intuitive way. There are several different kinds of techniques that allow to achieve this objective. The main technique used to perform this kind of task is called skinning and makes use of different structures in order to obtain mesh deformation that defines the character poses. Two popular skinning structures are the so-called cages and skinning-skeletons. A cage is an external structure that contains a three-dimensional mesh, and the deformation of such mesh is obtained by manipulating the cage vertices. A skinning-skeleton, instead, is composed of bones and/or joints and is an internal structure contained in a three-dimensional mesh. The deformation of the character mesh is obtained by applying geometric transformations to bones and joints.

Cages and skeletons have different expressive powers and different positive and negative aspects. Skeletons are usually used to perform articulation deformations, while Cages are usually used to perform volumetric deformations. This topic is discussed in details in section 2.

The definition of character poses is a time-consuming task, and consequently animators need simple and fast techniques that allow them to simplify the animation process. For this reason we want to define a new skinning technique, and our aim is to create a skeleton/cage hybrid that merges the expressive power of the skeleton with the one of the cage.

At the state of the art, there are two main works that address this kind of problem but both of them need to redefine the cage and the skeleton from scratch with some constraints. Our idea, instead, is to merge together already existing cages, with already existing skeletons, proposing an hybrid skinning paradigm. Our goal is also to develop a software tool that allows users to realize deformations using this paradigm. This tool must be fast, simple and more easy to use than other professional software used to realize deformations, like Maya or Blender. In this way, the animator is able to use at the same time both skeletons and cages to realize animations, simplifying the animation pipeline, reducing the animator workload and making the deformation process more intuitive and straightforward.

In section 3 we examine in details the related works discussed earlier, while, in section 4, the preliminary idea is explained.

2 Background

2.1 The Skinning process

In order to create an animation and bring a virtual character "to life" we need to produce a sequence of character poses, and we can identify several techniques used by digital animators that fulfil this purpose. One of the most popular techniques is the skeleton-based or cage-based skinning.

Usually, a three-dimensional character is a polyhedral structure called mesh composed of vertices, edges and faces. The faces can be composed of triangles, quads, general polygons, or a combination of all these.
The pose of the character mesh is obtained by deforming the mesh itself, moving all its vertices and, consequently, all the faces and edges. A mesh can be composed of millions of vertices and, in order to define a pose, manually edit every single vertex would be an impossible task for an animator, for this reason the skinning techniques were created.

The skinning process defines how the geometric surface of the character must deform, i.e. how its vertices (with faces and edges) must move, according to a function defined by deformation primitives [1] [2] (also known as handles). Those primitives are usually manually set up by a trained Digital Animator (called also as rigging artist) during a delicate and time consuming phase called rigging.

During the rigging phase, the artist specifies the influence of every single deformation primitive on every mesh vertex defining the so-called “weights”, so that the deformation of a handle will propagate to every single vertex proportionally to the amount of influence that the handle has on each single vertex.
The skinning weights can be computed automatically by using several techniques, or can be defined manually, with greater precision, by a rigging artist.

In synthesis, the skinning process is considered an essential task because it simplifies the whole deformation process. Indeed, it prevents digital animators from manually editing every single vertex of the mesh to make it move and allows them to simply associate a group of vertices to a single handle or multiple handles. This is necessary especially if we want to animate a very complex three-dimensional character composed of thousands or millions of vertices. For this reason it is clear that it is easier to manipulate single handles to obtain a deformation (needed to represent a pose) rather than a very large amount of vertices.

Deformations can be performed through different kinds of deformation primitives, and according to the structure of those primitives, we can talk of skeletons or cages, whose advantages and disadvantages must be taken into account according to the morphology of the digital character. In some contexts, the choice of a specific handle deeply simplifies the work of the animators and enables them to improve the graphical result.

In the next paragraphs the details of cages and skeletons are discussed, and further information about all the skinning techniques can be found in [1] and [2].

2.2 Skeletons

A skeleton is a structure contained inside the character skin. It is usually composed of bones and/or joints: the first ones represent the rigid parts of a character and the second ones are usually placed in the character articulation. In a skeleton-based skinning setup, bones and joints can be used as handles to create the deformation and propagate it to the character skin vertices using automatically generated or manually defined skinning weights. So, skeletons usually represent the articulated portion of a digital character. (Fig. 1)

There are several techniques that make use of skinning skeletons in order to perform skin deformation (surveys can be found in [1] and [2]). The most popular one is the Linear Blend Skinning, also known as skeleton-subspace deformation [4] [5], where every skeleton handle (bone or joint) is represented as a spatial transformation matrix $T_j \in \mathbb{R}^{3x4}$ and, therefore, we are able to define a deformation of the character skin using the following formula:

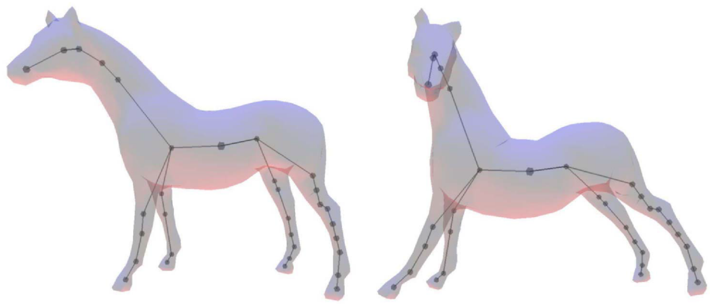

Fig. 1. Example of a skeleton inside a mesh. The spheres represent the joints, while the lines are the bones. Resting position of the skeleton (left). "deformed" position (right). (Source [3])

$$v'_i = \sum_{j=1}^{m} w_{i,j} T_j v_i \tag{1}$$

where v'_i represents the "deformed" position of the i-th character vertex v_i, and T_j is the manipulated transformation of the j-th skeleton handle, and $w_{i,j}$ is the handle weight, or the amount of influence of handle j on skin vertex i. In this way, we are able to define the character poses by manipulating the skeleton transformations. (Fig. 2)

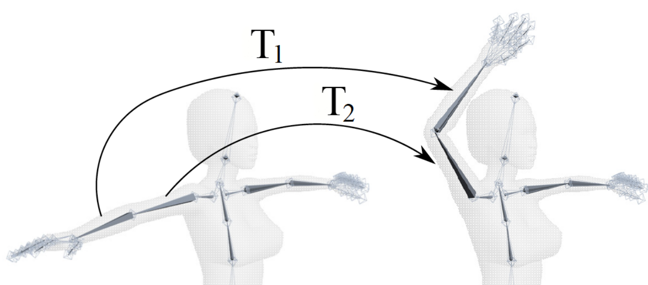

Fig. 2. Example of bone transformation achieved through the manipulation of the bones transformation matrices T_1 and T_2. (Source [2])

Unfortunately, Linear Blend Skinning presents visual artifacts like volume loss, self-intersection and the so-called "candy-wrapper" artifact, caused by the linear interpolation of the transformation matrices.

Another popular skeleton-based skinning technique is called Dual Quaternion Skinning [6]. Rather than using a rigid transformation matrix to perform transformation, DQS makes use of the dual-quaternions theory [7] to perform rotations and translation, that has a more robust behaviour with interpolation. For this reason, DQS solves the "candy-wrapper" problem but, at the same time, it creates the so-called "joint bulging" artifacts. (Fig. 3)

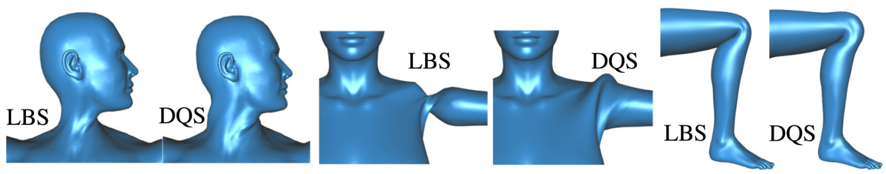

Fig. 3. A comparison between Linear Blend Skinning and Dual Quaternion Skinning. We can observe the "candy-wrapper" artifact for the LBS, and the "joint bulging" artifact for the DQS. Source [8] and [1])

2.3 Cages

A cage is a simplified (coarse) version of the mesh it represents and it should preferably have a small number of vertices. It can be seen as a low-resolution abstraction of the character. It is completely external to its mesh and envelops it, and it represents the mesh morphology.
In a cage-based skinning setup, the cage vertices can be used as handles to create the deformation and propagate it to the character skin vertices by using barycentric coordinates as weights.
The cage-based skinning deformation derives directly from the Free Form Deformation [9] that offers an intuitive and smooth control over the character skin by only using lattice control points (Fig. 4), but this technique does not take into account the character morphology. In fact, for complex mesh like a character articulated with several limbs, FFD becomes difficult or impossible to use in order to obtain a significant and meaningful deformation.
Cage-based deformation, instead, is based on the concept of generalized barycentric coordinates, through which we are able to express the position of every character vertex in relation to its cage vertices. There are several definitions of barycentric coordinates such as Mean Value [11], Positive Mean Value [12], Harmonic [13], and Green Coordinates [14]. Each one has pros and cons, and a comparison between them is available in [15]. Those barycentric coordinates represent the influence weight $w_j(v_i)$ that each cage vertex c_j has on a mesh vertex v_i, and can be computed in pre-processing.

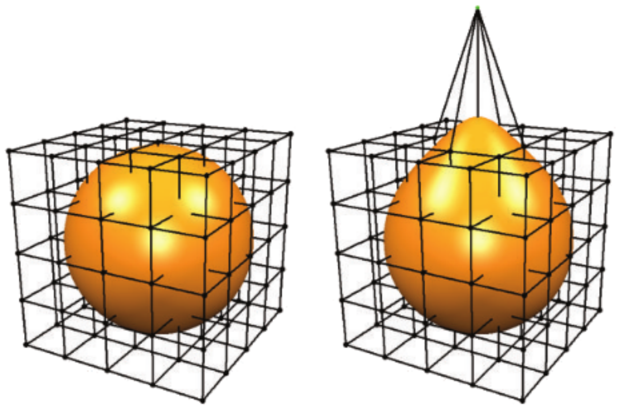

Fig. 4. Example of Free Form Deformation (Source [10])

The barycentric coordinates $w_j(v_i)$ must satisfy the following property:

$$v_i = \sum_{j=1}^{m} w_j(v_i) c_j \tag{2}$$

so, during the cage-based skinning process, we are able to define a deformation of the character skin by using the following formula:

$$v'_i = \sum_{j=1}^{m} w_j(v_i) c'_j \tag{3}$$

where v'_i represents the "deformed" position of the i-th character vertex v_i, and c'_j is the manipulated position of the j-th cage vertex c_j, also called the cage handle. In this way, manipulating and moving the cage vertices, we are able to define the character poses. (Fig. 5)

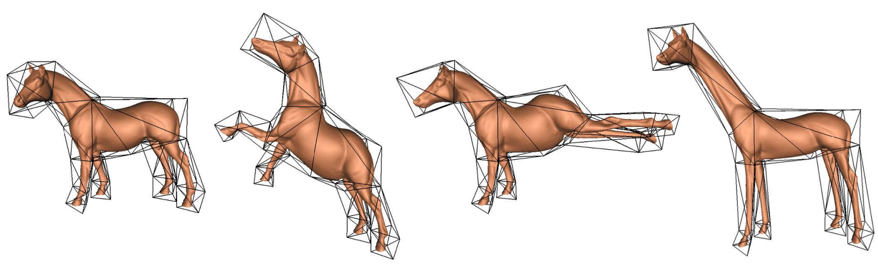

Fig. 5. Deformation of a horse character using the cage-based skinning. Resting pose on the left, deformed pose in the other pictures. (Source [11])

2.4 Skeletons plus Cages

Skeletons and Cages have different expressive powers and it is paramount to an animator's work to choose the most appropriate one, as it can both simplify the process and yield better results.

Skeletons are very useful and intuitive to use for articulated characters such as humanoids. In fact, in order to move an arm, we simply need to manipulate the single bone that represents the arm itself. Instead, using a cage, we need to move all the cage handles that envelope the arm. So, with the skeleton a single handle is needed, while, in the other case, we need to manipulate multiple handles to perform the same deformation.
Vice-versa, cages are very useful for volumetric deformation. For example, if we want to animate a bouncing ball enveloped in a square-shaped cage, we need to only move the top handles of the cage to obtain the deformation and the compression of the ball. Instead, using a skeleton, this would be a less intuitive task because the most trivial skeleton representation for a ball would be a single handle placed in the centre of it, so we need to define more complex and less intuitive skeletons, with extra bones and joints, to perform a similar (but not equal) deformation obtainable with a simple cage. Also, if we want to animate a breathing character, we can not accomplish this by using a skeleton. Instead, with a cage, we are able to obtain the breathing effect by simply moving the portion of the cage defined around the character's chest.
So, because of the different expressive power, the choice between a skeleton and a cage can lead to a reduction or to an increase of the rigging and skinning efforts based on the type of animation we want to realize. For this reason, the definition of a skeleton/cage hybrid paradigm can merge together all the positive side of skeleton and cages, allowing the animator to use both of them at the same time seamlessly, simplifying and making the animation process more intuitive, and reducing the workload for a digital artist.

3 Related works

At the moment, there are two main contributions to the skeleton/cages merging for skinning purposes.

The first one is the method proposed by Ju et al. with the cage-based skinning templates [17]. This work aims to create a skinning algorithm that allows to perform deformations that are replicable on multiple characters using a skeleton/cage hybrid.
In this method the skeleton is rigged to a cage and drives the motion of the cage vertices. In details, given the character mesh and a skeleton, the algorithm creates a full cage from "templates", partial cages associated to a particular skeleton part. Then, manipulating the skeleton handles, the algorithm will deform the associated cage using a particular deformation function similar (but different) to Linear Blend Skinning. Then the deformation will be propagated

from the cage to the character skin using Mean Value Coordinates as barycentric weights.

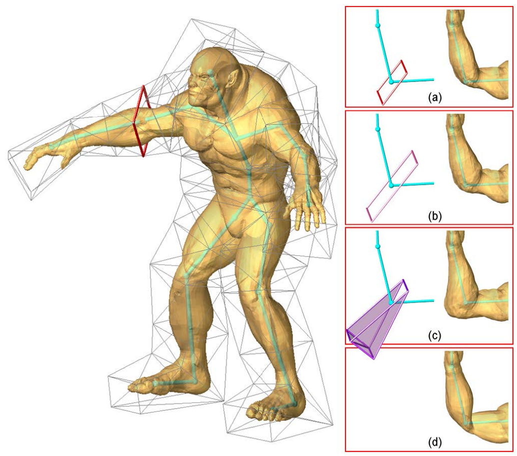

Fig. 6. Example of deformation using a cage constructed from different skinning templates (a), (b), (c), and the same deformation using the Linear Blend Skinning directly from the skeleton (d). In the last picture the "candy-wrapper" effect is noticeable. (Source [17])

The main purpose of this work is not to merge together the expressive power of skeleton and cages but to create volume preserving deformations using skeleton handles, overcoming the "candy-wrapper" artifact typical of the Linear Blend Skinning algorithm. (Fig. 6) So, in this case, we do not have a true skeleton/cage hybrid because it is not possible to interact directly with the cage handles to perform the deformation. In fact, to create a pose, the artist must interact only with the skeleton handles and the cage is used only the define the skin deformation. Also, the cage must be generated ad-hoc from the associated skeleton, so previously modelled and rigged cages can not be used. Furthermore, all the previously computed skeleton skinning weights must be dropped because the skeleton will be rigged directly to the cage vertex using a specific function rather than directly to the character skin.

The second method is the one proposed by Jacobson et al. with the Bounded Biharmonic Weights [16]. This work aims to make the digital animator free to use every kind of skinning primitive it prefers, like skeleton handles, cage handles or simple points to perform two-dimensional or three-dimensional character deformation. They give a definition for automatically computed skinning weights that can be used simultaneously and seamlessly with the three types of skinning structures listed earlier.

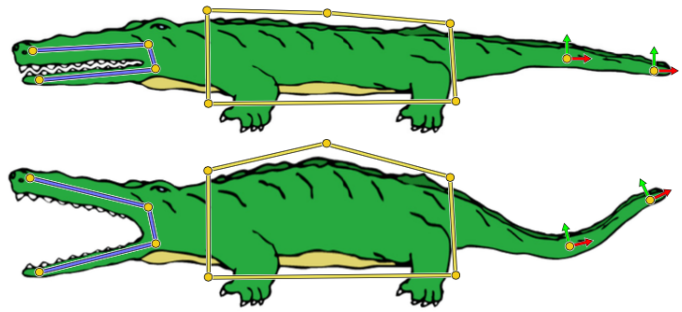

Fig. 7. Example of deformation simultaneously using skeleton, cage and generic handles, with bounded biharmonic as skinning weights on a two-dimensional character. (Source [16])

Despite the very good graphical result for the deformation (Fig. 7), the digital artist must necessarily use the bounded biharmonic as skinning weights, so previously computed or manually generated skinning weights can not be used, and all the pre-existing skeleton and cages must be rigged again with the new automatically generated weights.

4 The preliminary idea

The proposed idea is to formalize a skeleton/cage hybrid that unifies the expressive powers of the skeletons with the ones of the cages. In this way, animators have the freedom to use one kind of skinning primitive rather than the other based on the kind of pose or animation they want to achieve. In fact, as discussed earlier, for articulation deformations, like a humanoid walking or moving its arms, skeleton is the best choice. Instead, for volumetric deformations such as muscle bulging or thinning, a man breathing or a ball bouncing, cage is the best choice.

This new unified skinning paradigm must be weight agnostic, in fact, in order to simplify the rigging phase, we want to enable animators to use pre-existing rigged skeletons with pre-existing rigged cages, using the already defined weights for each structure. By using this approach, in a production studio, there is no need to effectively create a skeleton, cages or weights from scratch, but an animator can simply adapt the skinning algorithm to operate simultaneously with the previously defined ones.

In details, if we observe the linear blending equation for skeletons (eq. 1) and the linear blending equation for cages (eq. 3) we can observe several similarities (as observed also in [16]), in fact we can treat a T_j skeleton transformation (defined by the relative bones or joints), and a c_j cage vertex (that represents the cage

handle) as the same kind of generic handle h_j.
The idea is to formalize a skinning equation like the following one:

$$v'_i = \sum_{j=1}^{m} a_{i,j} h_j \tag{4}$$

where $a_{i,j}$ is an"agnostic skinning weight" derived directly from the already defined ones in the cage and in the skeleton. To do this, we need to find a "bilateral relation" or a mapping between the cage weights and the skeleton weights, and consequently between the skeleton and the cage. In synthesis, we want to obtain a function f that, given a cage weight w_{cage} and a skeleton weight w_{skel}, provides an "agnostic" weight a usable on both cage and skeleton:

$$a = f(w_{cage}, w_{skel}) \tag{5}$$

So, our purpose is to be able to perform a simultaneous and seamless manipulation of all the generic handles h: the manipulation of the cage handles will result in the deformation of the character and of the skeleton and, vice-versa, the manipulation of the skeleton handles will result in the deformation of the character and of the cage. For example, if the animator wants to animate a running man representing also the character's breath, he can use the skeleton handles to define the movements of arms and legs, while using at the same time the cage handles to represent the breathing animation. Also, we want to be able to constrain the movement of the cage based on the constraints defined on the skeleton. In fact, if the skeleton bones are constrained to rotation only and can not be stretched, the relative portion of the cage can not be stretched either. Moreover, constraints defined on the cage must reflect on the skeleton deformation.

In synthesis, the three main aspects we have to fulfil are:

- Understand how the manipulation of skeleton handles drives the motion of the cage handles.
- Understand how the manipulation of cage handles drives the motion of the skeleton handles.
- Choose what kind of skinning formula defines the physical deformation of the character's skin.

The second task is the most particular because, while the skeleton movements can be reproduced by the cage, this is not true if we switch cage and skeleton. In fact, breathing, bulging or bouncing animation can not be obtained easily (if not at all) with skeletons so we have to understand how these animations obtained with cage handles affect the skeleton handles. (Fig. 8)
For the third task, instead, we have to understand if we obtain a better skin deformation by only using the skeleton-based skinning formula (eq. 1), only using the cage-based skinning formula (eq. 3) or using some form of combination of

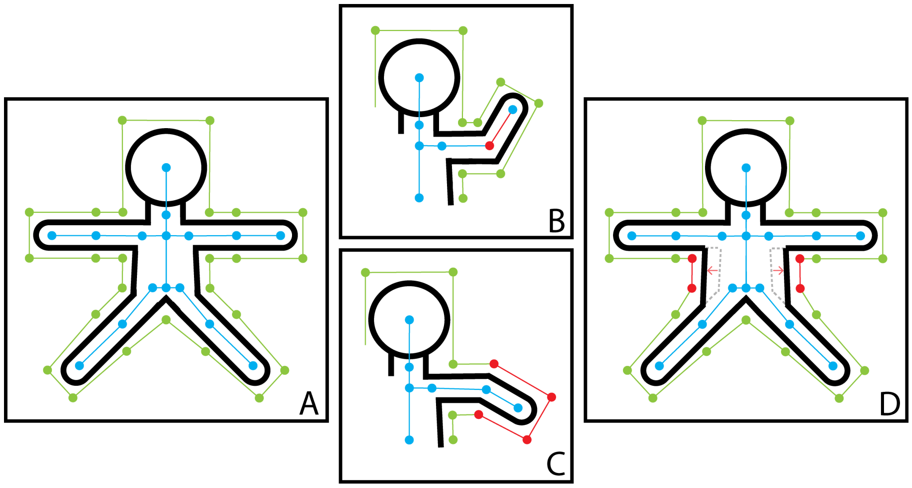

Fig. 8. An example of how our tool should work. (A) Given a character mesh in its rest pose, its rigged skeleton and its rigged cage, (B) moving a skeleton handle, the skin and the cage must deform and move accordingly. (C) Vice-versa, the manipulation of cage handles must drive the motion of the skeleton in a coherent way, deforming also the character skin. (D) Note that not all the cage movements corresponds to a skeleton movement, like for a breath animation.

both of them.

The fundamental and novel aspect of this idea is that it does not require to define a totally new ad-hoc cage, or ad-hoc skeleton, and is not limited or bounded to a particular type of skinning weight. In this way, the animator can define poses for the animation in an intuitive way, using the appropriate type of skinning handle, avoiding the need to define extra bones or joints in skeletons to obtain complex animations, and streamlining and simplifying the animation pipeline.

In the final phase of the project we plan to evaluate the usability of the developed tool, measuring the User Experience while realizing deformations and character poses. We want also to compare the UX against professional software like Maya and Blender, measuring the ease of use and the cognitive load.

5 University doctoral program context

I am Fabrizio Corda, a PhD student at the Department of Mathematics and Computer Science at University of Cagliari. My work is being conducted into the CG3HCI Lab, the Computer Graphics and Geometry Modelling supervised by the Prof. Riccardo Scateni and followed by Dr. Marco Livesu. I have started my PhD in October 2016 and I plan to defend my thesis in early 2020. My research field is about computer animation and skinning techniques.

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