Contact Skinning

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Abstract

In this paper, we propose a new approach to model interactions through a skinning method. Skinning is a frequently used technique to animate a mesh based on skeleton motion. In the case of a hand motion sequence used to manipulate and grasp virtual objects, it is essential to accurately represent the contact between the virtual objects and the animated hand. To improve the level of realism, our approach allows to accurately solve friction contact laws. In addition, contact constraints defined on the surface of the hand can be applied onto the skeleton to produce plausible motion. We illustrate our work through two examples: the real-time simulation of a grasping task and a character animation based on motion capture.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Animation and Virtual reality

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1. Introduction

In computer animation and virtual reality, reproduction of human interactions with the environment is often a target. Motion capture or data glove provide a simple way to produce realistic motions on animation characters and interactions with a virtual environment. For simplicity, the body (or some part of the body, like the hand) is modeled using an articulated skeleton. The resulting degrees of freedom to be tracked during the motion and to be animated are reduced to the minimum. Then skinning method [Blo02] allows to apply these motions to a surrounded deformable mesh, which is the skin of the body.

In this work, we aim at modifying the tracked motion of the skeleton according to contact constraints, like the ones involved during grasping. One issue is to modify the behavior of both skeleton and manipulated objects in a coupled way. This coupling necessitates to introduce physical models of contact and friction to obtain a realistic result.

The issue of computing contact forces for grasping has been addressed in computer animation [KP06] or virtual reality [BDB94] [WLGP04] [BI05]. However, these approaches have two main drawbacks: the contact detection and response are not based on a skin mesh of the hand but on articulated rigid bodies placed on the skeleton; moreover, stable virtual manipulation of deformable objects is not possible.

The main contribution of this paper is a new contact model based on skinning that permits to apply on the skeleton a set of friction contact constraints that are defined on the skin surface. Using an iterative solution, friction contact laws are solved with a good precision and without using penalty, projection methods or discretization of the friction cone. The algorithm is based on a Gauss-Seidel approach [JAJ98] [DDKA06]. However, we improved its convergence using the previous step result as an initial guess. The presented approach provides a stable grasping, with no interpenetration of both rigid and deformable objects.

2. Previous work

In computer animation, plausible and fast animation of deformable objects is often obtained using a surface skin attached to an articulated skeleton. Research work on skeletal animation has led to several algorithms for defining realistic skinning functions [WP02] [Kv05] as well as for handling external constraints [Gle98]. Among these constraints, collision with other objects has a great importance for a large part of animations and is a challenging issue. In [Can93], contact is handled by deforming the implicit field of the skin and a collision force is transmitted to the skeleton. In [GOT*07], Lagrange multipliers are used to compute a collision response and avoid interpenetration. However, these methods, that handle contact on the surface skin, are not based on accurate contact and friction laws. On the other hand, some methods present accurate friction contact model on articulated structure, like [KP06], but the external shape of the skeleton is a set of rigid bodies.

The method we propose in this paper combines accurate contact modeling with friction and a skinning approach to produce realistic behavior of skeleton-based animations.

3. Overview

Our method is based on skeleton configuration sequences, given by a motion tracking (even in real-time), or based on keyframe animation. When there is no contact, these configurations entirely lead the motion of the skin mesh. In contact case, we create a *ghost* configuration for the skinning model (with both skeleton and skin) that is constrained outside the surface of the objects (see figure 1). The unconstrained configuration is named *free* whereas the *ghost* one is the final configuration which is visualized. The physical model is reduced to a simple stiffness, placed at each articulation, between its free and constrained positions. A proximity detection adapted from [JW04] to deformable models allows to detect contact points on the skin and on the grabbed object. Then, the parameters used in friction contact equations are transfered to the coordinates system of the skeleton using direct and transposed relations of skinning kinematic. Therefore, we are able to build the Non-Linear Complementarity Problem (NLCP) that is based on contact (Signorini) and friction (Coulomb) laws. This NLCP is solved using the iterative approach employed in [DDKA06], that is improved using an initial guess on the contact forces. At each time step, the contact forces are stored with pairs of contacting primitives. These contact forces are reused as an initial guess if the same primitives are still in contact. We show that it significantly reduces the computation time.

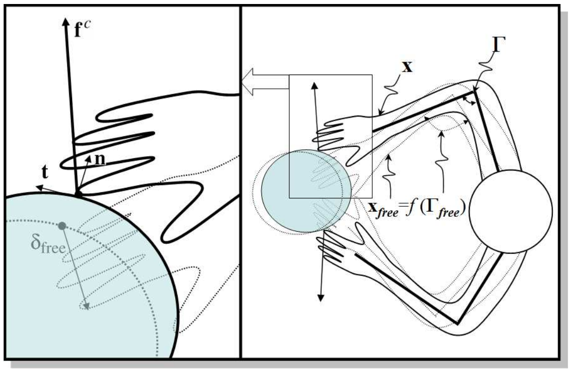


Figure 1: Contact skinning method. *From a skeleton configuration sequence* $\Gamma_{\mathbf{free}}$, *a correction* Γ *is computed so that the skin mesh behavior* $\mathbf{x}$ *follows friction contact laws when comes into contact. So, the contact parameters* $\mathbf{n}$, $\mathbf{t}$, $\mathbf{f}^c$, δ_{free}, *are defined at the skin level and then transmitted to the skeleton.*

4. Contact space through skinning

This section describes how the friction contact space is built coherently through skinning function. It is initially defined on the skin, using friction contact laws along the normal and tangential directions. Then, contacts are transfered and solved at the articulation level using "reverse" skinning functions.

4.1. Friction contact parameters

The contact and friction laws are based on the relative motion between colliding objects and the contact force. Both of them are defined along the normal $\mathbf{n}$ and tangential $(\mathbf{t},\mathbf{s})$ space of the contact.

Let's consider a contact point c between an object and the skin. In the following, $\boldsymbol{\delta}^c$ denotes the 3D vector from the position of the point on the object and the position of the point on the skin. $[{}^n\delta^c\ {}^t\delta^c\ {}^s\delta^c]$ are the coordinates of vector $\boldsymbol{\delta}^c$ in the frame $(\mathbf{n},\mathbf{t},\mathbf{s})$. When contact occurs, the position of the point is common to the colliding objects, then $\boldsymbol{\delta}^c = \mathbf{0}$ and let $\mathbf{f}^{\,c}$ be the force applied on the skin by contact c (see figure 1).

The contact model indicates that there is complementarity between the gaps ${}^n\delta$ and the contact forces ${}^n\mathrm{f}$ along the normal direction, that is:

$$0 \le {}^n\delta \perp {}^n\mathrm{f} \ge 0 \tag{1}$$

With the Coulomb's friction law, the contact force lies within a spacial conical region whose height and direction are given by the normal force, giving two complementarity conditions for stick and slip motions.

$$\begin{aligned} &[{}^t\delta\ \ {}^s\delta] = \mathbf{0} \Rightarrow \|[{}^t\mathrm{f}\ \ {}^s\mathrm{f}]\| < \mu\,\|{}^n\mathrm{f}\| && \text{(stick condition)} \\ &[{}^t\delta\ \ {}^s\delta] \neq \mathbf{0} \Rightarrow [{}^t\mathrm{f}\ \ {}^s\mathrm{f}] = -\mu\,\|{}^n\mathrm{f}\|\frac{[{}^t\delta\ \ {}^s\delta]}{\|[{}^t\delta\ \ {}^s\delta]\|} && \text{(slip condition)} \end{aligned} \tag{2}$$

To solve friction contact laws at the skin level, we need to relate the motion at the contact level to the kinematic equation of the skin. First, the value of interpenetration distance $\boldsymbol{\delta}^c_{\mathrm{free}}$ is evaluated using the relative distance, after collision of the detected contact points on each model. This vector gives the motion at the contact level if no contact force is applied.

If a contact occurs between the skin and an object at point α, the relative motion $\boldsymbol{\delta}^\alpha$ depends on $\boldsymbol{\delta}^\alpha_{\mathrm{free}} = \mathbf{x}^\alpha_{\mathrm{free}} - \mathbf{y}^\alpha_{\mathrm{free}}$ (where $\mathbf{x}^\alpha_{\mathrm{free}}$ and $\mathbf{y}^\alpha_{\mathrm{free}}$ are the position of point α on the skin and on the object during the free motion). It also depends on $d\mathbf{x}$ and $d\mathbf{y}$, the respective displacement of the skin and of the object due to contact forces:

$$\boldsymbol{\delta}^\alpha = \boldsymbol{\delta}^\alpha_{\mathrm{free}} + d\mathbf{x}^\alpha - d\mathbf{y}^\alpha \tag{3}$$

In our approach, the displacement of the skin fully depends on the skeleton motions. Thus, we need to write the relations between $\boldsymbol{\delta}$ and the degrees of freedom of the joints as well as between $\mathbf{f}$ and the corresponding torque and forces.

4.2. Skinning kinematics

The skin is a triangular mesh whose motion is driven by the skeleton using skinning functions. Skinning functions are used to obtain the corresponding position of the skin:

$$\mathbf{x} = \mathbf{F}(\Gamma) \tag{4}$$

where $\mathbf{x}$ is the vector of skin points position and Γ the articulation coordinates of the skeleton. In this work, we use the skinning function proposed in [Blo02] but the method can be extended to other skinning functions that can be written in the form of equation 4.

From the free configuration, we can compute a kinematic relation between the skin mesh and the joint motions:

$$d\mathbf{x} = \frac{d\mathbf{F}}{d\Gamma}(\Gamma)\Delta\Gamma \tag{5}$$

The originality of our approach lies in the use of the skin mesh for the contact surface: contact detection and response are computed at the level of this surface. The interaction treatment computes forces on the contact points of the skin. Equation 5 provides the direct kinematic model of the skin, we use the inverse model to transfer the contact forces $\mathbf{f}$ to the joints of the skeleton. This inverse model is provided by the transposed Jacobian $\mathbf{J}^T$ of the skinning function:

$$\tau = \mathbf{J}^T\mathbf{f} \tag{6}$$

where τ is the torque created on joints by contact forces and $\mathbf{J} = \frac{d\mathbf{F}}{d\Gamma}$. Then, we apply elastic equations to the skeleton between its *free* configuration and its *constrained* configuration Γ.

$$\tau = K \cdot (\Gamma - \Gamma_{\text{free}}) \Leftrightarrow \Gamma = K^{-1}\tau + \Gamma_{\text{free}} \tag{7}$$

K is a stiffness applied at each joint. Using the new configuration Γ, we can compute the constrained position of the skin points $\mathbf{x}$

$$\mathbf{x} = \mathbf{x}_{\text{free}} + \mathbf{J}(\Gamma - \Gamma_{\text{free}}) \tag{8}$$

A recent work [KP06] suggests to measure both motion and contact force during motion capture, in order to identify the quasi-static model used for an articulated hand. These measures are perfectly compatible with the quasi-static model of the skeleton used in our work.

4.3. Contact space compliance

To describe the mechanical behavior of the skeleton during contact, the mechanical coupling between the different contact points on the skin must be modeled. This information is provided by evaluating the mechanical compliance matrix, called Delassus operator, of the skeleton on the contact space $\mathbf{W}$. The use of this operator will be described in the following section.

Each friction contact creates three nonholonomic constraints along the normal and tangential directions. Let's consider the constraint α created on the skin point i along the direction $\boldsymbol{\alpha}$ (with $\boldsymbol{\alpha} = \{\mathbf{n}, \mathbf{t}, \mathbf{s}\}$).

The constraint direction can be transfered at the level of the skeleton joints using the transposed kinematic relation 6:

$$\tau_\alpha = [\mathbf{J}^T]\boldsymbol{\alpha} \tag{9}$$

This computation is performed in two steps, as described by fig 2. Since only few joints k of the skeleton are influenced by this inverse kinematic relation, the vector τ_α can be stored in a sparse form. To obtain the Delassus operator between this constraint and another one β, we simply compute:

$$\mathbf{W}_{(\beta,\alpha)} = \sum_k \tau_\beta^k \left(\frac{1}{K^k}\right) \tau_\alpha^k \tag{10}$$

where K^k is the stiffness of joint k. This computation is also optimized using the sparsity of the vector $\boldsymbol{\tau}_\alpha$. Given the Delassus operator $\mathbf{W}$ for all constraint directions, the skinning model can be added to a physically based simulation for the computation of friction contact response.

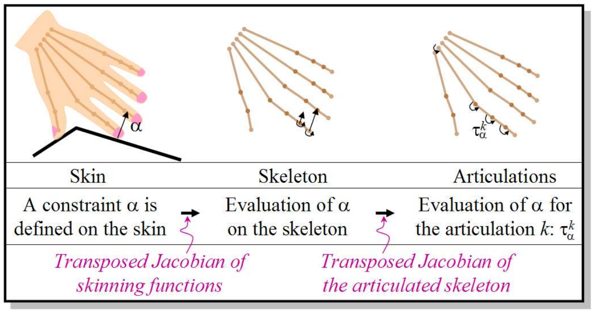


Figure 2: Transfer of constraints. *First, the constraint direction is transfered to the skeleton via transposed skinning functions. Then it is transfered to skeleton joints using standard computation on articulated structure.*

5. Contact response computation

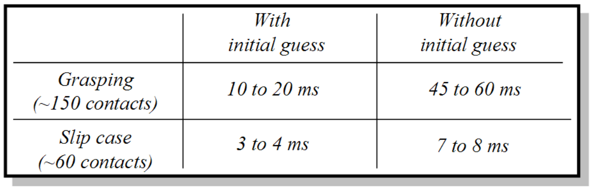
The computation consist in finding the friction contact forces that respect Signorini and Coulomb laws. Several works [JAJ98] or [DDKA06] present Gauss-Seidel iterative approaches that solve this problem. It necessitates the computation of $\mathbf{W}$ for all contacting objects. The computation for rigid objects and for linear FEM objects is described in [DDKA06],.

Considering a contact α, among m contacts, one can write the behavior of the model in contact space:

$$\underbrace{\delta_\alpha - [\mathbf{W}_{\alpha\alpha}]\mathbf{f}_\alpha}_{\text{unknown}} = \underbrace{\sum_{\beta=1}^{\alpha-1}[\mathbf{W}_{\alpha\beta}]\mathbf{f}_\beta + \sum_{\beta=\alpha+1}^{m}[\mathbf{W}_{\alpha\beta}]\mathbf{f}_\beta +}_{\text{frozen}} \delta_\alpha^{\text{free}} \tag{11}$$

here $[\mathbf{W}_{\alpha\beta}]$ gives the mechanical coupling between contact points α and β. On each contact α, Gauss-Seidel method consists in solving the contact and friction laws, by considering the contribution of other "frozen" contacts ($\alpha \neq \beta$). We perform this algorithm until convergence, i.e. the displacement on the contact space between two iterations is inferior to a given threshold. The threshold is chosen small to obtain a good precision on the solution of the Signorini and Coulomb laws, but it increases the number of iterations.

However, using the temporal coherency of the simulation, we can provide an initial guess to the Gauss-Seidel algorithm which speeds up its convergence. The previous contact force solutions and directions are stored with a reference on the contact point location on each object.This location is described by the two primitives (triangle, segment or point) on which the point lies. If a contact point is detected with the same primitives as a contact point of the previous step, we reuse the computed friction contact force as a guess for the new contact. During grasping task, when objects are highly constrained by a large number of contacts, this initial guess provides an important speed-up (see figure 3). Indeed, in that case, the primitives in contact are usually the same from one step to another. In case of slip, the number of contacts is usually smaller which makes the initial guess less important.



	With initial guess	*Without initial guess*
Grasping (~150 contacts)	*10 to 20 ms*	*45 to 60 ms*
Slip case (~60 contacts)	*3 to 4 ms*	*7 to 8 ms*

Figure 3: Computation time table. *Computation time for solving contacts with and without the initial guess. For each case, we use the average of 100 successive computations. The results are the minimum and maximum values obtained on 10 similar cases of grasping and slip.*

6. Examples

6.1. Interactive simulation of Grasping

The first application of the method is virtual reality where a virtual hand is a simple and direct way for interacting with a virtual environment. We demonstrate that using our method, a model of the hand based on skinning is able to grasp and manipulate objects. To satisfy virtual reality constraints, the simulation must be computed at interactive rates (around 20 FPS), which is achieved for models with medium complexity (1500 triangles for the cow model presented in figure 4).

Figure 4: grasping simulation

6.2. Character animation

We use this method to modify a sequence of a character animation based on contact constraints. The character motion is provided by a sequence of skeleton postures that are applied to the skin of the character via skinning function. Based on the mechanical properties (like mass, see fig 5) of colliding object, the motion of the character is adapted in order to follow contact and friction laws. It provides a simple and direct way to create physics based animations.

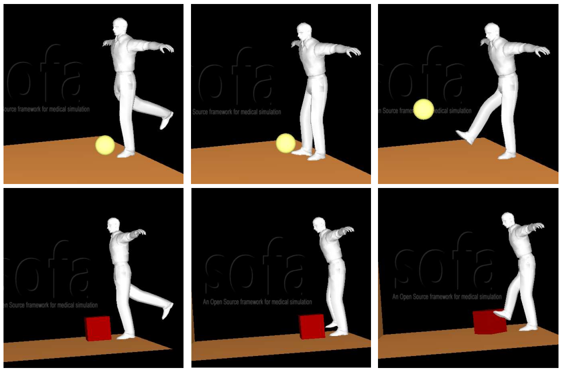


Figure 5: Character animation *Based on the same sequence, the behavior of the character is automatically adapted when shooting on a light object or on a heavy one.*

7. Conclusion and Future work

In this paper, we present a method to handle multiple contacts with friction on a skinning mesh driven by a skeleton motion. Friction and contact laws are defined on the skin and their resolution provide a correction on the skeleton behavior. In the future, we will investigate a more efficient initial guess of the contact forces, based on the neighborhood of the contacting primitives.

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