Haptic Rendering of Deformable Surfaces in Medical Training

A. F. Abate, A. Casanova, M. Nappi, S. Ricciardi

Abstract. *Haptic systems applied to medical simulation and training can provide users with crucial kinaesthetic and tactile info otherwise impossible to convey. As the typical objects involved in this kind of simulation are very often deformable tissues, one of the main challenges in this area is the perceptually believable reproduction of these structures through haptic rendering techniques. In this paper we propose the use of a colour or grey scale bitmap to associate local deformability info to the geometry. This approach allows the visual-haptic engine to modulate the resistance to compression exerted by the simulated tissues based to a local parameter. By using multiple layers of textures or animated textures, locally non-linear or even dynamic behaviours can be simulated with a low computational load. Preliminary experiments based on a Immersion Cyberforce hand-based haptic device are encouraging.*

Keywords: haptic systems, haptic rendering, simulation and training.

1. Introduction

Haptic systems have a remarkable potential for many applications, specially those involving a specific tactile know-how. Indeed, medical applications such as tele-surgery or surgical simulators may particularly benefit from haptic interfaces, but their efficacy depend on the realism of the visual-haptic perceptions provided to the system's user. To this regard the simulation of the contact with different structures or tissues characterized by different deformability (i.e. reaction to the contact forces) can represent one of the key advantage of haptic based interaction compared to conventional visual interaction, as it provides user with a level of info not derivable otherwise. Unfortunately, contact modeling in medical simulation is a challenging problem. The way contacts are handled plays a very important role in the overall behavior of the interacting objects. The kind of contact model adopted (including friction or not), highly influences the post-impact motion of the interacting objects. In most simulators with haptic feedback, the collision response of soft tissues with a virtual surgical instrument is assumed to be very local: the interaction only consider a single point [Mahvash and Hayward, 2004] [Mendoza et al., 2002].

The most popular approach is the penalty method which consists in defining a contact force f = k at each contact point where is a measure of the interpenetration between a pair of colliding objects, and k is a stiffness parameter. This stiffness parameter must be large enough to avoid any visible inter-penetration, however, its value cannot be determined exactly. In addition, if an explicit time integration scheme is used, and k is large, very small time steps are required to guarantee the stability. The quick growth of energy in the haptic control loop induced by the method often leads to excessive damping in the provided solutions. A possible improvement over the penalty method can be achieved through the use of an implicit integration scheme [Meseure, 2003]. Yet, solving the resulting stiff and non-smooth system can be computationally prohibitive when the objective is to reduce as much as possible the inter-penetration distance. Some methods, developed for force feedback applications are based on the avoidance of visible inter-penetration through constraint-based techniques. The collision can be prevented by geometrical deformation constraints like in [Picinbono, 2002] or [Forest et al., 2004], or by god-object [Zilles and Salisbury, 1995] and proxy [Barbagli et al., 2003] methods. Another way is the use of Lagrange multipliers, which are appropriate for handling bilateral constraints [Galoppo et al., 2006]. However, contacts between objects intrinsically define unilateral constraints, which means that physics is not always verified when using techniques based on Lagrange multipliers. As a consequence, colliding objects could stay artificially stuck at the end of the time step. Improvements over constraint-based techniques are possible by using a Linear Complementary Problem (LCP) formulation. The solution of the LCP gives an accurate description of the contact forces needed to zero out the interpenetration, and prevents objects to stick together [Pauly et al., 2004]. By expanding the LCP, or by using a non-linear solver, the formulation can be extended to model both static and dynamic friction for rigid [Anitescu et al., 1999] and deformable [Duriez et al., 2006] objects. Computationally efficient methods for solving linear complementary problems are proposed [Murty, 1997], thus making such approaches appealing even for interactive simulations.

Anyway, though contact modeling is a major concern in haptic systems, most of the methods described so far compute reaction force according to a stiffness parameter often defined at an object level (e.g. the whole object surface has the same stiffness) and even in case local stiffness parameters are available they approximate the real surface behavior with a very coarse granularity. The same consideration may be applied to the law which approximates the typically non-linear behavior of the object's surface when compressed: whatever the law adopted, it is the same for the whole surface.

Unfortunately, the consistency of many organic tissues is complex to describe at a global level and is often related to their healthy or pathological condition, providing crucial info to the specialist during palpation. As one of the main aims of visual-haptic simulators is to replicate the most faithfully possible the perceptual aspects of the interaction, we believe that a greater attention should be put to the simulation of those surface characteristics which may enhance the "haptic knowledge" of the system's users.

2. Map-based approximation of deformable surfaces

We propose a simple yet effective and efficient way to represent detailed information on local stiffness of a simulated surface by means of a dedicated bitmap providing a much greater accuracy than usual object-level attributes or even coarse array of parameters.

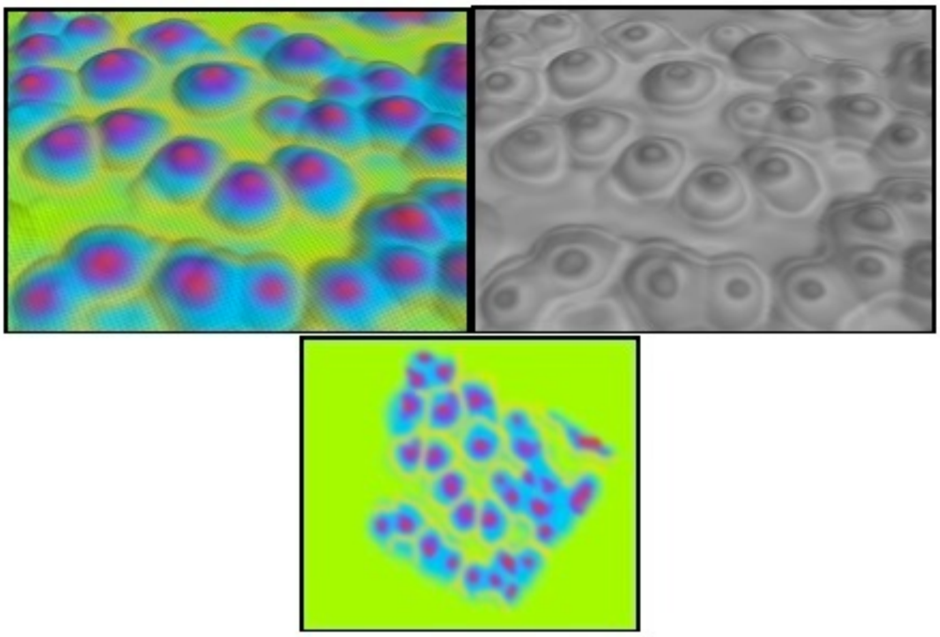

Figure 1
Color and grayscale deformability maps

Gray-scale
8 bit – 256 stiffness levels

Gray-scale
16 bit – 65536 stiffness levels

RGB		
8 bit – Surface level	8 bit – Subsurface level	8 bit – Inner level

Figure 2
Various arrangements for stiffness encoding in bitmaps, by grayscale or colour maps. The former provide local stiffness at a pixel level, the latter exploits three values per pixel to modulatet stiffness according to three level of depht.

The basic idea behind this proposal is to exploit texture mapping (typically used to simulate visual properties such as ambient and diffuse color, transparency, roughness, shininess, etc.) to associate local deformability data to 3D geometry. The local surface stiffness encoded by color at a texel level is then exploited by the haptic renderer to modulate the contact force feedback due to local tissue deformation resulting from interaction. More precisely, the deformability map is associated to mesh vertices through mapping coordinates in the form (u, v), previously projected onto the surface. The additional info can be represented through each pixel's RGB channels in a color texture or, in the simplest case, in a grayscale image, according to different arrangements offering a great flexibility of use (see Fig. 1). A deformability can be produced by a data driven methodology (for instance from image processing of diagnostic data or procedurally from anatomical models) or even by hand, by means of a 3D paint application.

In its simplest form an 8 or 16 bit grayscale image may encode the local stiffness parameters required to compute the reaction force at a texel level, thus providing a range of 256 or 65536 stiffness levels with a spatial granularity only depending by image's resolution. A 24 bit color image is able to arrange a more articulated set of data. Indeed it can store three 8 bit wide layers of stiffness data, enabling to simulate a non-linear surface behavior at a texel level. In other terms, it is possible to exploit the three (or even four if a 32 bit image is used) stiffness values associated to a given (u, v) position on the surface as a discrete approximation of the stiffness measured at a progressively greater depth (see Fig.2). Where required, by using multiple textures the approximation can be easily improved. As the deformability of a surface involves both visual and haptic feedback during simulation, but not necessarily these two channels (which in most applications are decoupled due to different frame-rate requirements) are supposed to share the same stiffness coefficient, mixed visual-haptic stiffness data may be embedded in the same 16, 24 or 32 bit deformability map (e.g. 8 bit visual + 8 bit haptic, or 16 bit visual + 8 bit haptic, or even 16 bit visual + 16 bit haptic). Moreover dynamic modification of the local stiffness can also be rendered by means of animated bitmaps or implementing a real time procedural processing of bitmap pixels in the RGB color space (e.g. a color shift may simulate a modification of the surface's deformation capability, see Fig.3). An additional advantage of this technique is related to its ultra-fast computing by means of modern GPUs. Indeed these vector processors can effectively process multiple very large (up to 8K pixel wide) textures on a single pass due to their highly parallel cores, while their dedicated VRAM (up to 4GB wide) could arrange many texture layers for each object in the virtual environment.

3. First experiments

The proposed technique has been experimented on a visual-haptic platform which is part of a wider research project aimed to the training of obstetricians to delivery [Abate et al., 2010]. A CyberForce® hand-based force feedback system by Immersion Corporation has been utilized in order to provide the user with haptic sensations during the simulated intervention. The Haptic Sub-System translates in terms of force feedback the output of the visual-haptic rendering engine, but it can also act as an input interface for function selection and command triggering. As motivated in *Section II.* the CyberForce® force feedback system by Immersion Corporation has been selected to provide the user with haptic sensations during the simulated intervention. The Cyberforce is composed by an articulated exoskeleton ending with a CyberGrasp system including a CyberGlove 22 sensors dataglove (see Fig. 4 and 5). The CyberGrasp provides the transmission of contact sensations to the operator's fingertips while the whole CyberForce simulates the weight and the inertia of the manipulated objects within its operative volume.

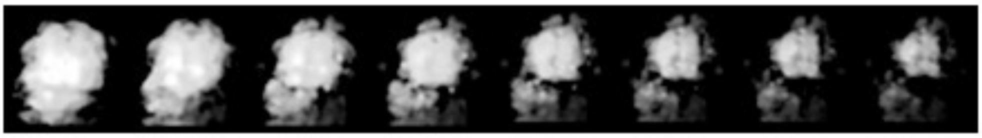

Figure 3
Animated map implementing spatial and temporal modification in surface stiffness

The weight of the grasped object can be rendered by the CyberForce through the application of a force on the back of the user's hand. The operator can, therefore, estimate the effort required to perform a particular task or the resistance opposed by a solid or deformable object with specific mass [Chryssolouris et al., 2000] since the penetration among objects gets cancelled by the reaction forces activated in relation to contacts among an polygonal object and the virtualized hand [Colgate et al., 1993]. This system is able to provide up to 8.8 N of force to the hand (through the CyberForce) and up to 12 N to each finger (through the CyberGrasp), values adequate to reasonably imitate the real forces involved during the delivery. It can also inherently measures hand's position and rotation (6 DOFs) with an accuracy of approx. one tenth of millimeter and one tenth of degree respectively. The main system limit, at least for our context of interest, is the lack of a torque feedback on the wrist and on the arm joints as well. This means that it can't replicate the resistance due to the rotation of an object (e.g. the child's neck) approximating its joint limits.

The test bed hardware included a dual quad-core Intel Xeon processor based Mac Pro workstation from Apple Inc., equipped with 8 Gigabytes of RAM and an Nvidia Quadro 5600 graphics board with 1,5 Gigabytes of VRAM. Overall the system's testers were positively impressed by quality of deformation of the simulated tissues (child's head and body, mother's perineal area), even if the quantity of deformation was sometimes inadequate to imitate actual plastic phenomenon due to the compression exerted on the child's head. Nevertheless the system capability to provide (via the deformability map and the related haptic rendering) different perceptions of the deformability of the structures handled through the haptic device, was appreciated and considered one of the strong point of the on-going research for a realistic delivery simulator.

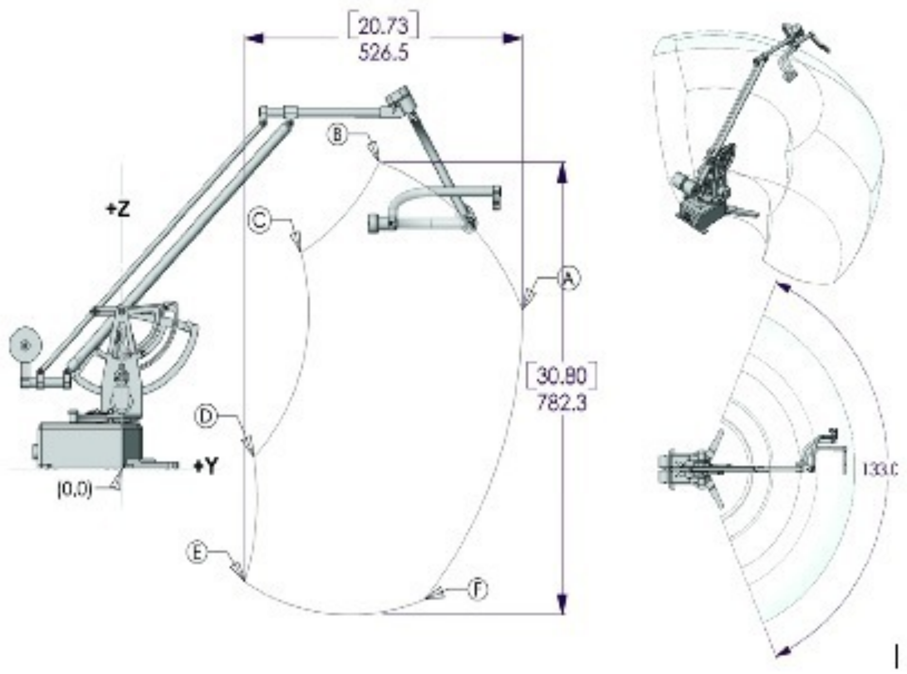

Figure 4
The Immersion CyberForce articulated exoskeleton and its operative volume.

4. Conclusions and future research

We presented a method to improve haptic simulation of deformable surfaces based on the use of a colour or grey-scale bitmap to associate local deformability info to the geometry. The proposed approach is computationally efficient as it involves simple calculations and it is inherently suited to be executed on GPUs. Its flexibility enable the approximation of non linear behaviour in the surface stiffness at a pixel level as well as for its dynamic modification. Besides performing an extensive testing of the proposed technique in different environments, we are exploring the possibility to use a 24 bit depth image to store a quantized stiffness vector (each RGB component is a vector component, instead of a single scalar value) which could be useful for improve surface deformation calculations during inter-object contact.

Figure 5
A view of the visual-haptic delivery simulator test-bed, featuring an Immersion CyberForce hand-based haptic device.

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Biographies

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