Physically Realistic Soft-Tissue Deformation in Real-Time

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Abstract

The use of haptics in virtual applications has become widespread in the last decade in several areas, especially in medical applications. After the integration of haptics, virtual medical simulations have been more popular than plastic tissue models or cadavers. Virtual environments are better for not only objective performance assesment but also creating desired scenarios in medical hands-on training. Besides various surgery scenarios can be created as well as surgery rehearsals by using patient specific data in virtual environments. However introduction of haptics into virtual simulations has also triggered new challenges in the area because of the high refresh rates needed for the haptics.

The sufficient refresh rate for the haptic force is 1 kHz such that discontinuity is not perceived by human sense. Besides the deformable objects need to be modeled in high complexity to provide realistic behaviour especially in surgery simulations. Therefore the simulation of deformable soft tissues with physically realistic force feedback in real time is still one of the big challenges in the haptics area. The major challenge is the computational burden to simulate realistic deformations which cannot be easily handled by using even today's fastest computers. A compromise between the realism and speed has to be achieved in the simulation of soft tissue deformation. There are two general methods followed in the literature: mass-spring and finite element models. Even though mass-spring models are easy to implement and sufficient refresh rates can be reached; the physical properties of materials cannot be taken into account and the model may respond un-realistically to larger deformations in these methods. Although the latest studies reveal that it is possible to simulate physically realistic deformations by using Finite Element Methods (FEM), the real time requirement is not easy to satisfy because of the complexity of this approach.

In spite of the computational load of FEM, it is still the most popular method to model physically realistic deformations for soft tissue. While it is easier to solve linear FEM equations in real-time, it is observed that soft tissues have non-linear behaviour, such that the linear deformation becomes un-realistic if the size of the deformation exceeds a threshold (typically 10% of the original tissue size). In addition to non-linearity, soft tissues may also have various complex behaviours like visco-elasticity and anisotropicity increasing the computational burden. If tissue cutting is also to be simulated, the model should be updated both physically and virtually, which makes the real time simulations even harder.

To reach a compromise between the necessity of high haptic refresh rates and the computational burden of the FEM, several optimization techniques such as condensation [Bro-Nielsen and Cotin 1996], pre-computation [Cotin et al. 1999; Sedef et al. 2006; Sela et al. 2007], level of detail [Debunne et al. 2001], and exploitation of the sparse matrix structure have been introduced in simulations. Current simulators, however, still have to either sacrifice one property of real tissues such as non-linearity, anisotropicity or visco-elasticity, or apply force interpolation or extrapolation techniques to reach a sufficient haptic refresh rate (1 kHz). Therefore solution of large FEM systems in real-time to be used in soft-tissue deformations is still a challenge for which new solutions are being sought.

Keywords: Soft tissue deformation, surgery simulation, FEM

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