Interactive Soft-body Simulation for Surgical Applications

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Figure 1: Real-time simulation of a spinal ligament (7k tetrahedral, left), and deformable beam (5k tetrahedral, right).

ABSTRACT

In this work, we explore an approach for physics-based simulation of soft bodies using Position Based Dynamics (PBD). Our approach is stable and efficient, achieving interactive framerates, even on mobile devices. We use strain constraints, inspired from the Finite Element Method (FEM), to simulate the physical behavior of deformable objects ranging from muscle tissue, bone, and human organs. We apply Anderson acceleration to our solver to boost the convergence for stiff materials. A graph coloring technique is also used to accelerate the convergence of our Jacobi solver. Our approach runs in real time on the GPU.

CCS CONCEPTS

• Virtual Reality • Training Simulator • Surgery

KEYWORDS

Soft-body simulation, Position Based Dynamics, Graph Coloring, Numerical Acceleration

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1 Introduction

Simulating soft bodies for surgical training is a challenging topic (Fig. 1). Trade-off between accuracy and efficiency is usually vital. Many methods that have been proposed to simulate the behavior of a deformable object, such as the FEM, are computationally expensive, making them prohibitive for use in real-time applications like surgical simulation. Hence the need for other methods like mass-spring models and shape matching which allow for fast approximation but have the drawback of limited control over the material behavior. In this work, we focus on a low computation budget method that offers a plausible accuracy and which can run on low-end devices at interactive rates.

2 Related Work

Position Based Dynamics (PBD) [1] is a constraint based method where the core idea consists of applying a set of hard constraints on particle positions and then maintain these constraints satisfied throughout the simulation by correcting particle positions. Originally, material stiffness required manual tuning to the scaling applied to displacement vectors used to correct particle position. Furthermore, because constraints are handled as hard constraints, increasing the number of iterations of the solver resulted in a stiffer behavior. This limitation was resolved by Macklin et al. [2] where a new parameter is used to limit the position correction with respect to the stiffness value. Moreover, continuum mechanics formulations were proposed by Bender et al. [3] and Macklin et al. [2] where control over material behavior is improved by using meaningful parameters such as Young's modulus and Poisson ratio.

3 Accelerated XPBD

In our work we use the XPBD [2] method to simulate soft body deformation. Strain constraints are projected in parallel

in a Jacobi fashion on the GPU using compute shaders. The constraint function is defined as the Green strain tensor, such that

$$\boldsymbol{C(x)} = \boldsymbol{\varepsilon} = \frac{1}{2}(\boldsymbol{F^T F - I}) = \begin{bmatrix} \boldsymbol{\varepsilon_x} \\ \boldsymbol{\varepsilon_y} \\ \boldsymbol{\varepsilon_z} \\ \boldsymbol{\varepsilon_{yz}} \\ \boldsymbol{\varepsilon_{xz}} \\ \boldsymbol{\varepsilon_{xy}} \end{bmatrix}_{\boldsymbol{Voigt}} \quad (1)$$

Updates to the Lagrange multipliers $\Delta\boldsymbol{\lambda}$ are computed by solving the linear system:

$$[\boldsymbol{\nabla C(x) M^{-1} \nabla C(x)^T} + \tilde{\boldsymbol{\alpha}}]\Delta\boldsymbol{\lambda_i} = -\boldsymbol{C(x)} - \tilde{\boldsymbol{\alpha}}\boldsymbol{\lambda_i}. \quad (2)$$

We correct the particle positions by adding the average of Δx_i:

$$\Delta\boldsymbol{x_i} = \boldsymbol{M^{-1}\nabla C(x)^T \Delta\lambda_i}. \quad (3)$$

The compliance is defined in terms of Young's modulus $\mathbf{E}$ and Poisson ratio allowing for accurate material control.

3.1 Graph Coloring

Although the Jacobi solver allows for a straightforward parallel implementation, it suffers from a low convergence rate. We employ a graph coloring method proposed by Fratarcangeli and Pellacini [4] where constraints are organized in groups of the same color. Within each group, the constraints are solved in parallel, whereas groups of colors are solved sequentially in a Gauss Seidel fashion.

3.2 Numerical Acceleration

One of the limitations of XPBD is that it requires a large number of iterations to converge especially when dealing with stiff materials [2]. We therefore tested two numerical acceleration techniques: Chebyshev acceleration [5] and Anderson acceleration [6]. Both methods improve the convergence of the solver. In Fig. 2, we show that for the same number of iterations, the Anderson acceleration is able to converge more quickly. The target strain is reached with fewer than 10% of iterations required without acceleration, as shown in Fig. 3.

4 Limitations

As depicted in Fig. 4, when using a large number of iterations with Anderson acceleration, we end up with a stiff material regardless of the Young's modulus value (i.e., strain=0). This is because our approach applies the acceleration on particles positions, rather than Lagrangian multipliers. Hence, we converge to the same solution as the PBD method. Future work will address this problem.

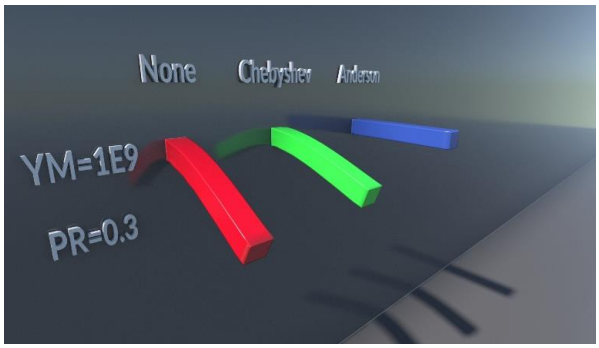

Figure 2: Simulation of stiff materials with and without acceleration techniques (40 iterations).

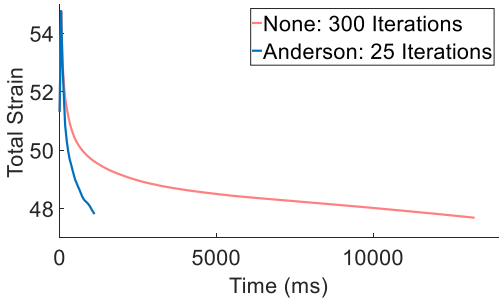

Figure 3: Solve time using Anderson acceleration (E = 1e9).

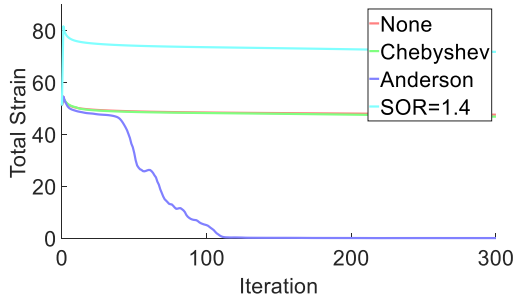

Figure 4: Convergence with acceleration (E = 1e6).

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