Physikalisch exakte Echtzeitsimulation deformierbarer Körper für OP-Training und Therapieplanung

Physically Accurate Real-Time Simulation of Deformable Bodies for Surgical Training and Therapy Planning

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Purpose

Today.s real-time operation environments almost exclusively limit themselves to small-scale local deformations, linear strain measures and soft material. Real-time and numerically stable simulation of non-linear as well as stiff volumetric bodies is computationally very challenging and has not yet been integrated into such environments. Virtual surgery simulators, on the other hand, need to incorporate real world physical parameters in order to be applicable to real world data and thus to increase the degree of immersion. In addition, local as well as global non-rigid transformations must be performed in real-time.

Method

To meet the constraints imposed by virtual surgery simulators, we propose a multigrid approach as a strategy for constructing a particular solver for the governing equations of elasticity theory. Based on a 3D finite element discretization, this approach allows us to combine non-linear strain measures and implicit time integration into a simulation support system amenable to real-time applications. Implicit time integration schemes are not susceptible to numerical instabilities as they are immanent to explicit schemes usually

employed in such simulators. Moreover, such schemes allow for the simulation of stiff material exhibiting real world elasticity constants.
The multigrid solver considers the deformable body at different levels of resolution, progressing the solution from coarse to fine thus minimizing the number of iterations required to solve the governing equations.
Physically accurate simulations are achieved by considering both the linear Cauchy strain measure and the non-linear Green strain measure (Figure 1). By using non-linear material laws, numerically stable simulation of large and global deformations is guaranteed.

Results

A simulation technique for volumetric deformable bodies is proposed, which is unconditionally stable due to implicit time integration and which can incorporate real world physical parameters (Figure 2). Our multigrid approach allows for the use in real-time applications like virtual surgery simulators.
If linear approximations are considered, we can simulate up to 25.000 tetrahedral elements with more than 30 fps on a single CPU. In the nonlinear setting, e.g. in case of global rotations or large deformations, this number reduces to a few thousand elements.
By means of this technique, realistic simulation of surgical interventions in parenchymatous structures will be greatly enhanced.

Conclusion

Physically accurate and stable simulation of deformable bodies, including global deformations due to inter-object collisions, is an ever increasing requirement in virtual surgery simulators. We have shown a multigrid approach to be an effective and efficient means for such simulations (Figure 3). Since the burden of the solution is partly put into pre-processing to build up large systems of equations, topology changes due to body destructions can not yet be simulated interactively. In addition, whole body non-linear simulation still reduces the number of elements to be simulated in real-time significantly. These limitations can be overcome by splitting the body into multiple connected parts, which are simulated separately. Only for the region being modified, non-linear simulations will be carried out - the remaining parts of the body can be approximated using linear strain. In this way, local destructions as well as real-time simulation of non-linear material can be achieved.

Figure 1: Comparison of the Green strain and the approximative Cauchy strain by means of a reference object (top left).
The first one produces correct deformations (top right) while the second one can lead to artificial forces (right).

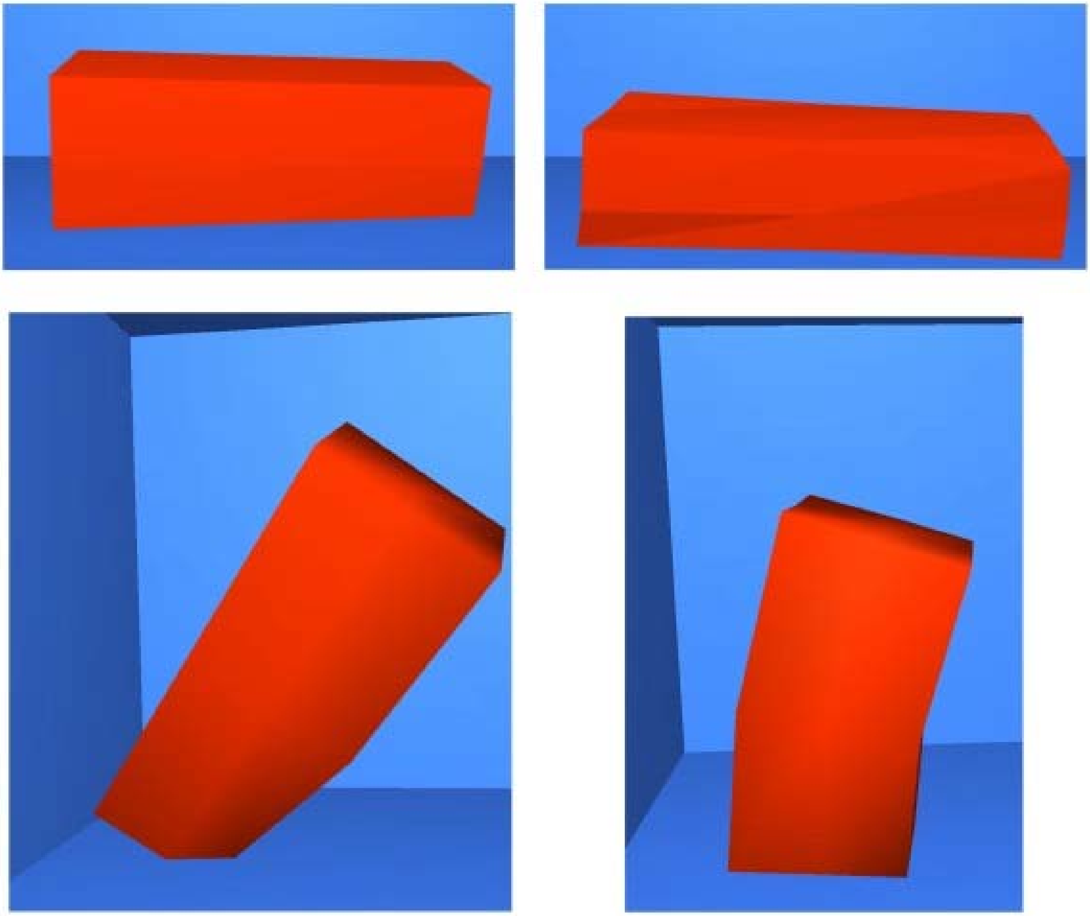

Figure 2: Interactive simulation of a reference object with different stiffness parameters. On the left, stiffer materials are simulated than on the right.

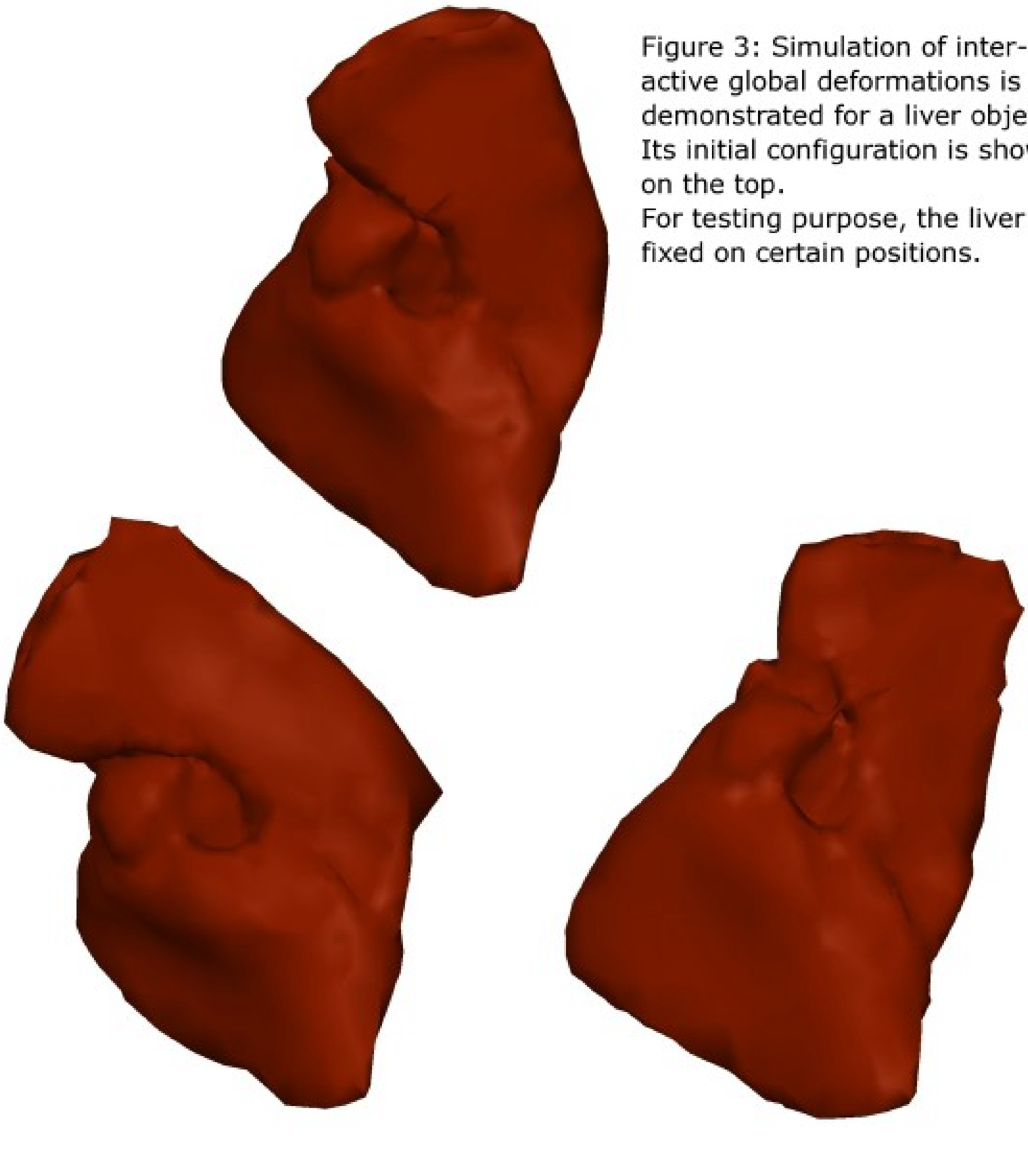

Figure 3: Simulation of interactive global deformations is demonstrated for a liver object. Its initial configuration is shown on the top.
For testing purpose, the liver is fixed on certain positions.