Simulating the Devolved: Finite Elements on WALL•E

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For the human characters on Pixar's WALL•E, an automatic system for secondary ballistic motion was needed to add an extra level of realism and to lighten the burden on animators. This task was complicated by the nonphysical nature of the underlying models; the secondary motion should look realistic even if the primary animation is exaggerated and stylized. To accomplish this, we used tetrahedral finite element simulation together with several control mechanisms to target the simulation pose towards the animation.

During pre-production, the human characters went through several stages of development. Early versions were made of transparent, gelatinous material instead of flesh, and were unrecognizable as humans. This posed interesting problems for animation and simulation. How does one act with a facial performance on a material with no real structure? How does the simulator preserve animation detail and still allow the material to undergo large deformation? As the story evolved the jelly creatures became more human, and the requirements of the simulator changed. Detail preservation grew easier as key details in the face and hands were now adjacent to bones and required less secondary motion, but maintaining animation silhouettes elsewhere in the body became more important.

1 Finite Element Simulation

The initial character designs of the devolved humans involved extreme deformations for both primary and secondary motion, so our simulator had to behave smoothly and robustly in situations with many degenerate and inverted tetrahedra. We therefore chose to use the finite element method of [Irving et al. 2004] for the internal physics of the material as opposed to a mass-spring system. Finite elements also enabled us to capture the incompressible and biphasic nature of biological tissue. Biphasic response allowed the material to be soft enough for interesting surface rippling but harden under large deformation to avoid undesirable mesh collapse. These phenomena are difficult to capture with mass-spring models.

Starting from an animation sequence defined only on a surface mesh, we needed to add dynamic secondary motion without deviating from animation poses when the character was not moving. In particular, static poses had to be well matched even though the shapes from animation were not physically based. At the same time, the simulation had to take over and deform the character radically under sufficient external impulse. To achieve this, we first diffused the target animation to the interior vertices of the mesh by solving a Laplace equation discretized on the tetrahedra using the surface animation as a boundary condition. We then applied two complementary control mechanisms: a system of soft constraints pulling each simulated point towards its target, and a direct modification to the rest state of each tetrahedron to match the current shape of the animation. With constraint forces alone the large changes in shape between different poses of the character would be constantly fought by the finite element forces in the simulation, smoothing out deformation around joints and adding creases in undesirable places. Continuously altering the rest state allowed the simulation to respect these natural shape changes without damping out interesting dynamic motion. The deformation gradient between the original and modified rest state was clamped in logarithmic space to avoid sliver tetrahedra in extreme poses.

The soft constraint springs were integrated implicitly to allow their stiffness to be ramped arbitrarily high to match animation exactly in certain areas of the mesh. Since the springs at different points are independent this did not require a linear system solve. All other integration was explicit for the elastic forces and implicit on the damping forces to preserve detail in the simulation.

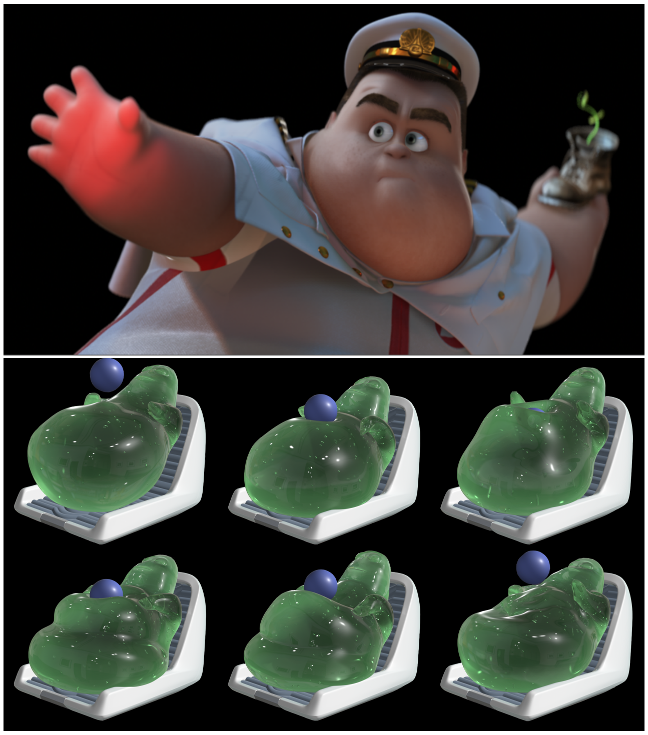

Figure 1: *Final and early versions of animated characters with simulated secondary motion. ©Disney / Pixar. All rights reserved.*

2 Pipeline

We built a streamlined interface for animators to run simulations and interactively adjust results. Real time kinematic colliders were used to give animators direct feedback during interaction with objects, and the same geometry was then fed to the simulation for dynamic collisions. Spatially varying material properties were mapped from surfaces to the mesh interior via a Laplace equation and then adjusted with a volumetric paint tool. All simulations were run in parallel using MPI.

Most simulations involved one or two characters and were restricted to adding only secondary motion. In shots with large crowds of interacting humans, the simulator also controlled the global position and orientation of each character. Animators created a variety of stationary animation cycles, and the position, orientation, and momentum of the animation were continuously adjusted to match the simulation before targeting forces were applied.

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References

IRVING, G., TERAN, J., AND FEDKIW, R. 2004. Invertible finite elements for robust simulation of large deformation. In *Proc. of the ACM SIGGRAPH/Eurographics Symp. on Comput. Anim.*, ACM, 131–140.

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