Modeling and Animation of Complex Mechanical Phenomena

Looking for the right models and algorithms

Miguel A. Otaduy

URJC Madrid

http://www.gmrv.es/~motaduy

This talk will cover most of our work on modeling and animation of various mechanical phenomena (deformations, contact, liquids, fracture), with an emphasis on the use of data and how to optimize or machine-learn models from that data.

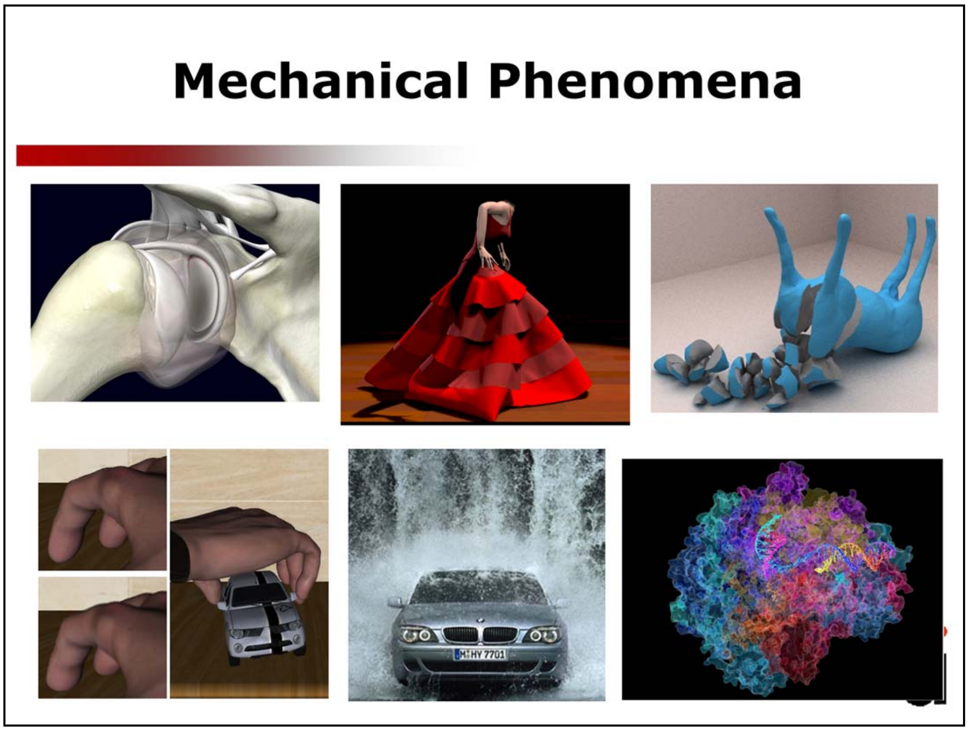
Short Bio

Electrical Engineering 2000, Mondragón (Spain).

PhD Computer Science 2004, UNC Chapel Hill (US).

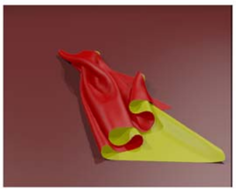
Research assoc. 2005-2007, ETH Zurich (Switzerland).

Prof. 2008-…, URJC Madrid (Spain).

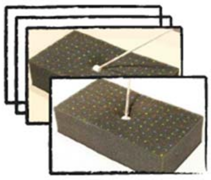


Here's a range of mechanical phenomena that we're looking into and their applications: organ deformations for medical training and planning, cloth simulation for animation or fashion, fracture mechanics for animation, biomechanics for virtual touch, liquid simulation for animation, and molecular dynamics for drug design.

Research Topics



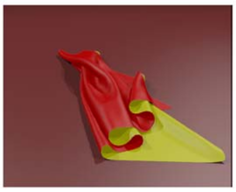
Constrained Dynamics



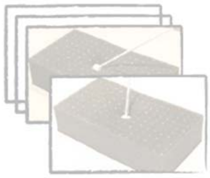
Data-Driven Modeling

The talk begins with an overall description of constrained dynamics, which is the underlying model we use to simulate mechanical effects. Then, it covers the use of data for modeling purposes.

Research Topics

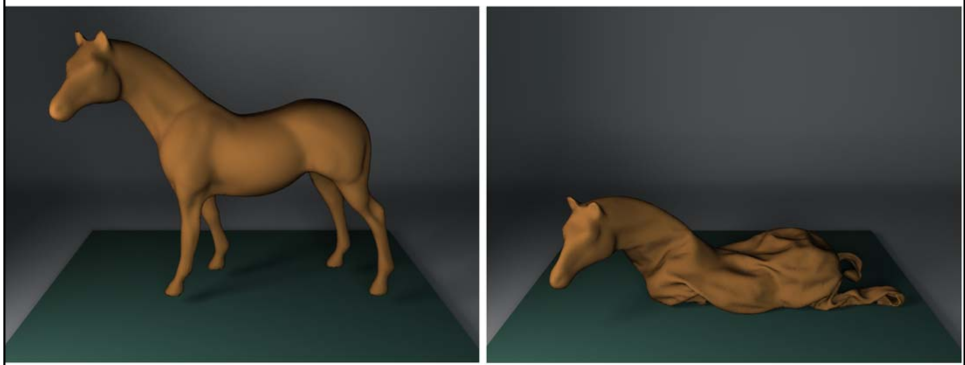


Constrained Dynamics



Data-Driven Modeling

Deformations and Contact



Most of our work deals in some way with modeling object interactions through contact. This is an example of efficient handling of self-contact.

Schvartzman et al., ACM SIGGRAPH 2010.
http://www.gmrv.es/Publications/2010/SPO10/

LCP: Linear Compl. Problem

$$\mathbf{Au} = \mathbf{b} + \mathbf{J}^T\lambda$$
$$\mathbf{Ju} \geq \mathbf{d}$$
$$\lambda \geq 0$$
$$\lambda^T(\mathbf{Ju} - \mathbf{d}) = 0$$

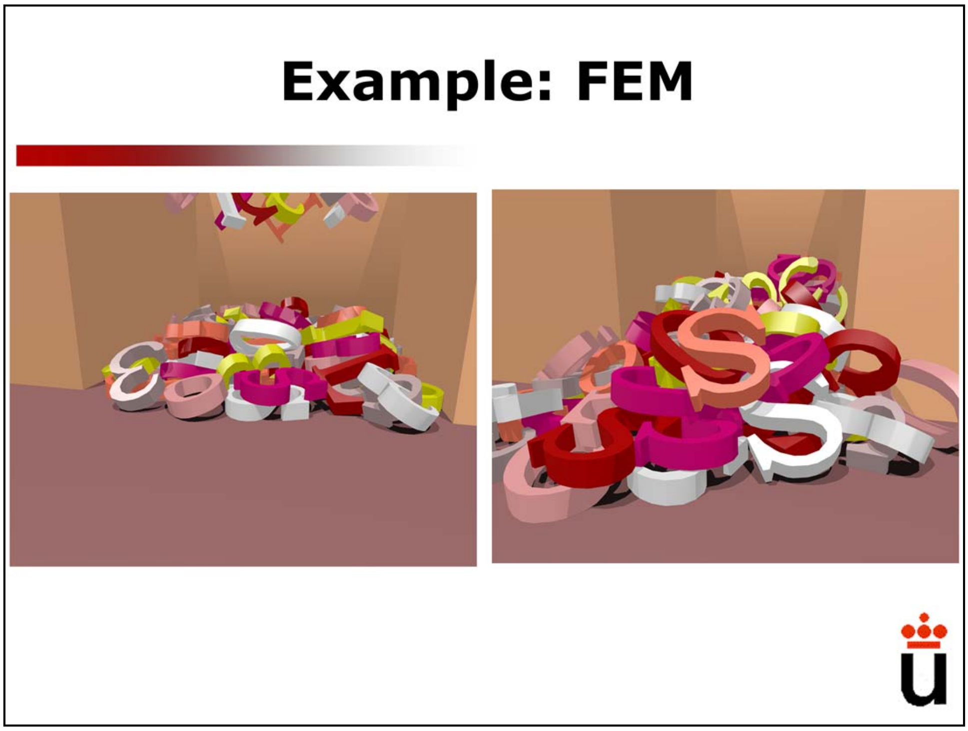
Constrained dynamics can be formulated as a linear complementarity problem (a type of QP):

A * u = b describes numerical integration of dynamics, which reduces to solving a linear system per simulation frame. u is the new set of object velocities.

Constraints (such as contact) are added as J * u >= d, and solved thanks to Lagrange multipliers.

The last equation indicates that contact forces or constraint gaps need to be 0; they can't both be positive.

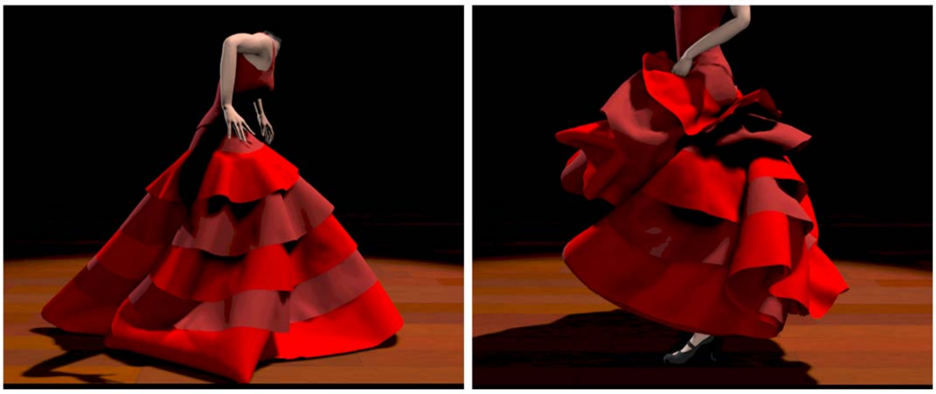
An LCP is a complex problem, and much of our work in constrained dynamics is to find efficient models with minimal complexity for particular applications.



Example application of the LCP formulation to contact with finite element simulation of deformations. The example is interactive with aprox up to 10 letters. The whole simulation took 90min. Handling of friction is particularly nice.

Otaduy et al., Eurographics 2009. http://www.gmrv.es/Publications/2009/OTSG09/

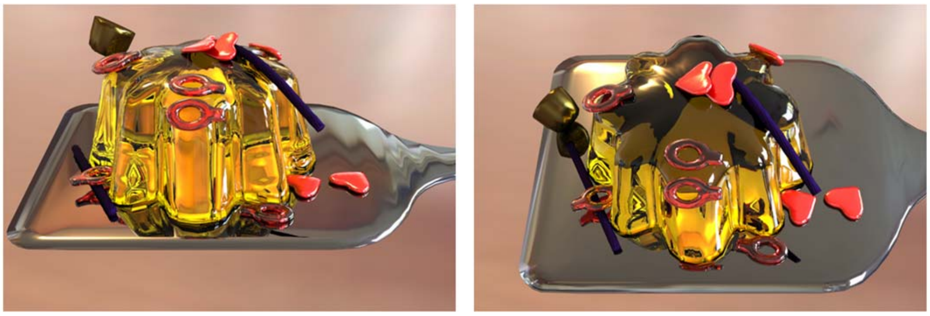
Example: Cloth



Same approach applied to self-contact in cloth animation. This example was provided by Disney Animation Studios. They didn’t have a robust method to simulate this example at the time. It took 15h.

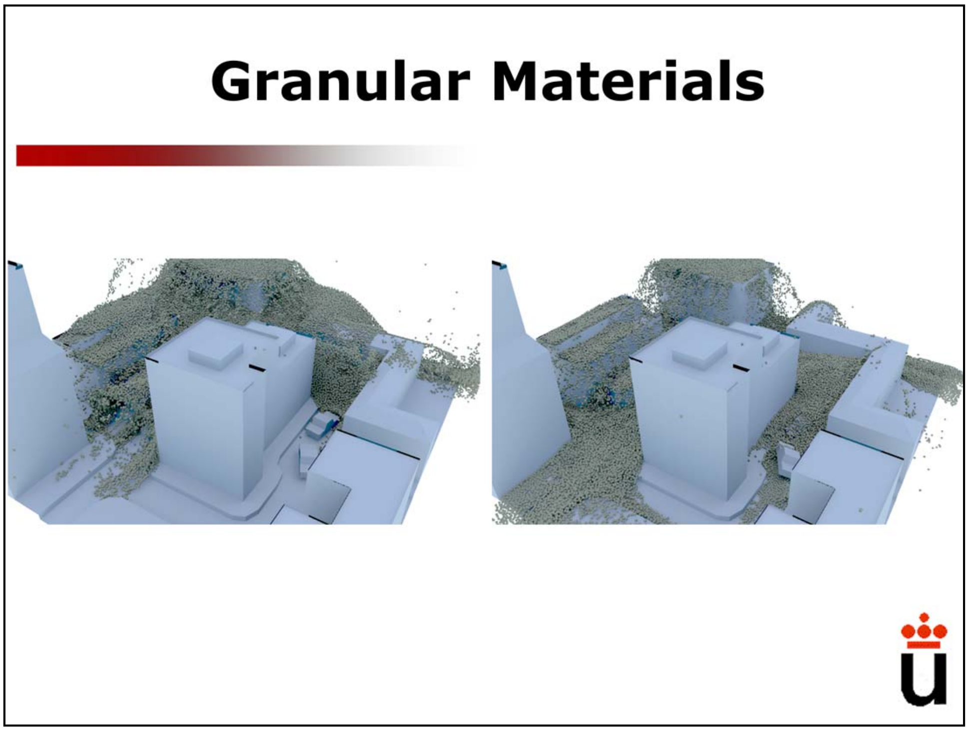
Otaduy et al., Eurographics 2009. http://www.gmrv.es/Publications/2009/OTSG09/

Adhesion as Constraints



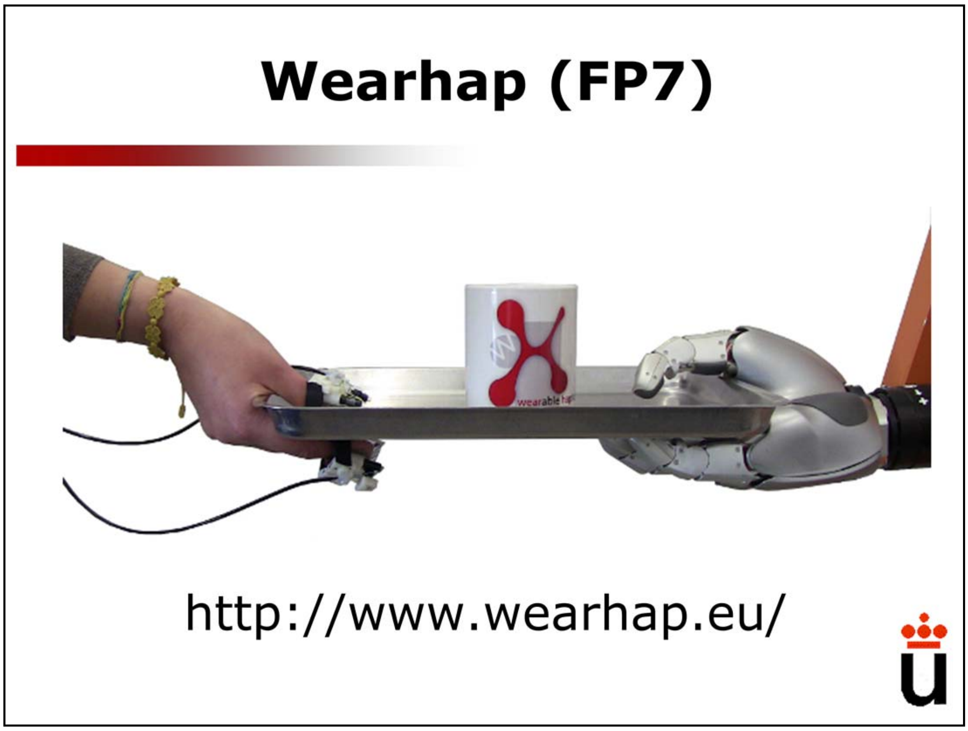
But many more effects can be incorporated into a constrained dynamics formulation. Here, we included modeling of adhesion.

Gascón et al., ACM Symposium on Computer Animation 2010. http://www.gmrv.es/Publications/2010/GSO10/



Even granular materials can be simulated using constrained dynamics. The governing equations are Navier-Stokes, with a modification of incompressibility constraints to handle granular-like expansion and friction constraints.

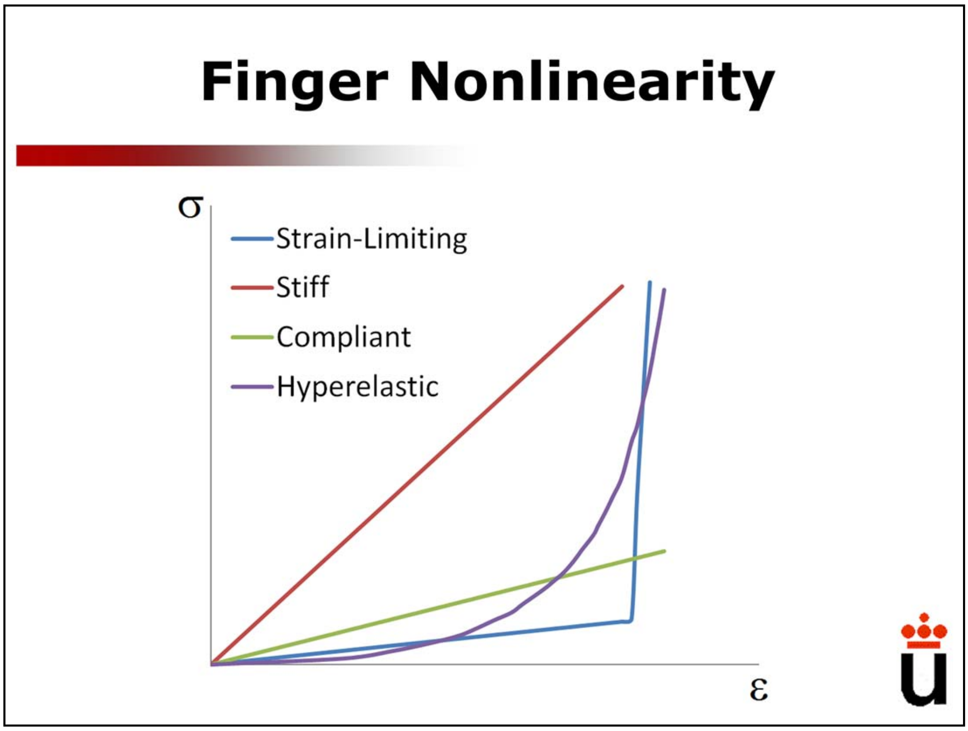
Alduán et al., ACM Symposium on Computer Animation 2011.
http://www.gmrv.es/Publications/2011/AO11/



One of the major projects we are involved in is Wearhap, a collaborative European project for the design of wearable haptic devices (virtual touch). Our role in the project is to develop biomechanical models of human touch for two purposes: one is to understand the process of touch through stimulation of mechanoreceptors in the skin, the other is to compute forces and motions to be displayed by haptic devices in real time.

http://www.gmrv.es/layoutGMRV.php?name=Projects/Wearhap/prueba_en.html

http://www.wearhap.eu/



When modeling biomechanics of touch, it is critical to accurately represent the nonlinearity of human skin (shown as the hyperelastic curve in the figure). Instead of using linear material models, the traditional efficient solution in computer graphics, we use strain-limiting. We model deformation limits using constraints in a constrained dynamics framework.

Strain-Limiting Constraints

- Strain and deformation gradient

$$\epsilon = \frac{1}{2}(\nabla \mathbf{u} + \nabla \mathbf{u}^T) = \frac{1}{2}(\mathbf{G} + \mathbf{G}^T) - \mathbf{I}$$

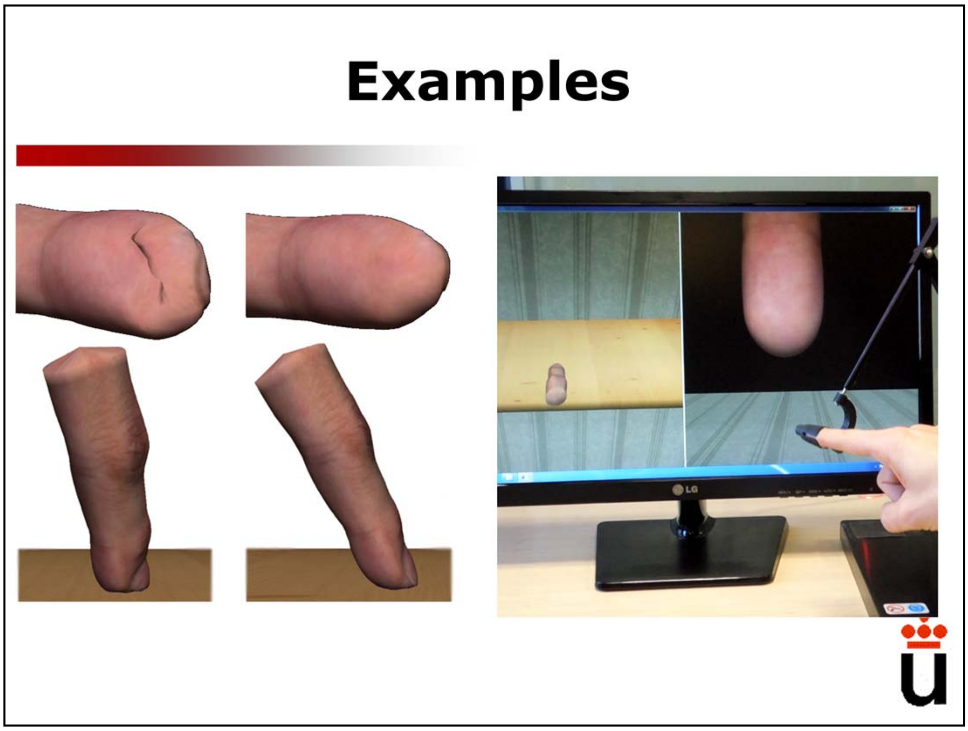
- SVD of deformation gradient

$$\mathbf{G} = \mathbf{USV}^T \quad \Rightarrow \quad \mathbf{S} = \begin{pmatrix} s_1 & 0 & 0 \\ 0 & s_2 & 0 \\ 0 & 0 & s_3 \end{pmatrix} = \mathbf{U}^T\mathbf{GV}$$

- Strain-limiting constraints

$$s_{\min} \leq s_i \leq s_{\max}$$

Much of the challenge comes from formulating constraints and solving them efficiently. This requires the computation of derivatives of constraints with respect to the degrees of freedom of the simulation. In this particular case, this requires the differentiation of SVD computations.

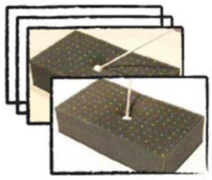


The leftmost column shows artifacts due to the use of linear material models (model inversion under friction, or collapse under compression); the center column shows results with our constraint-based formulation. The rightmost image shows our system in use in an interactive haptic simulation.

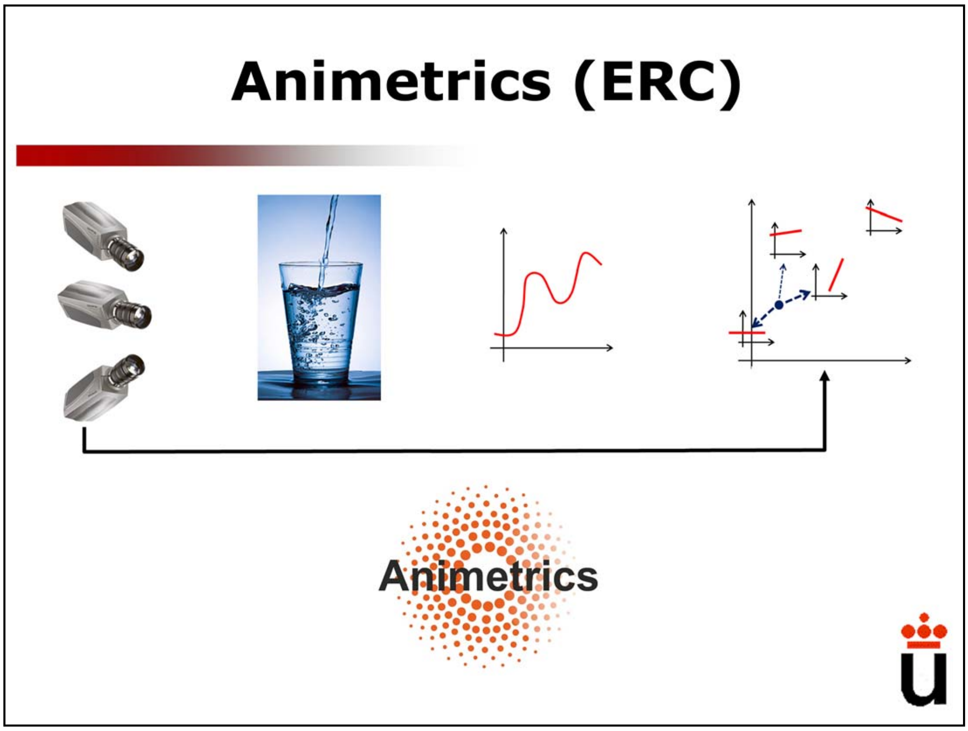
Perez et al., IEEE World Haptics Conference 2013.
http://www.gmrv.es/Publications/2013/PCHGO13/

Research Topics

Constrained Dynamics

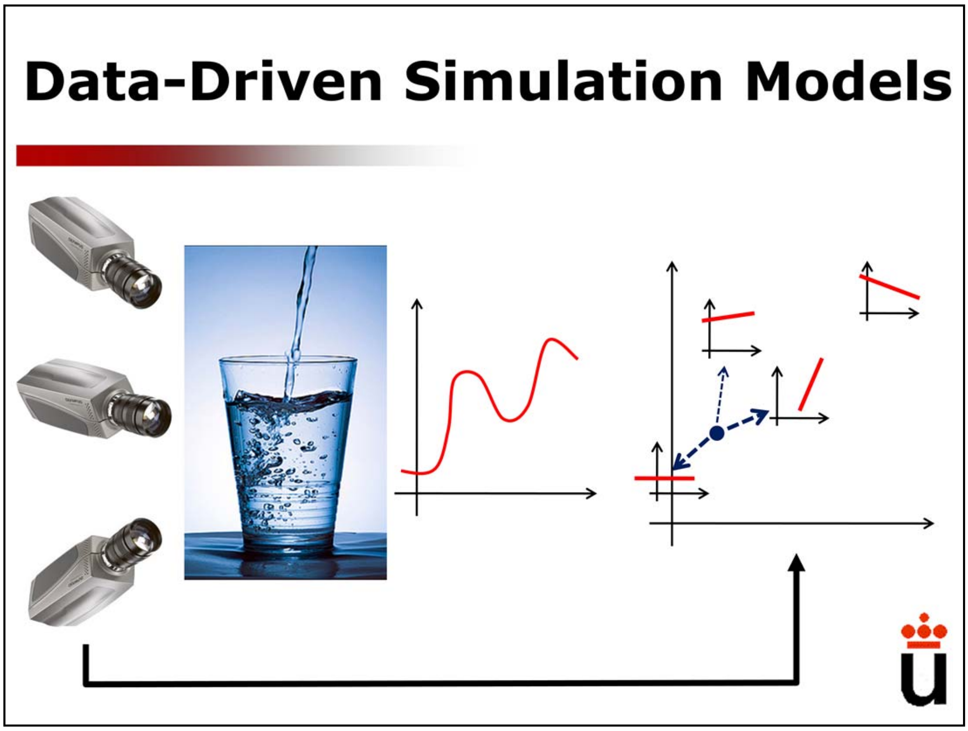


Data-Driven Modeling

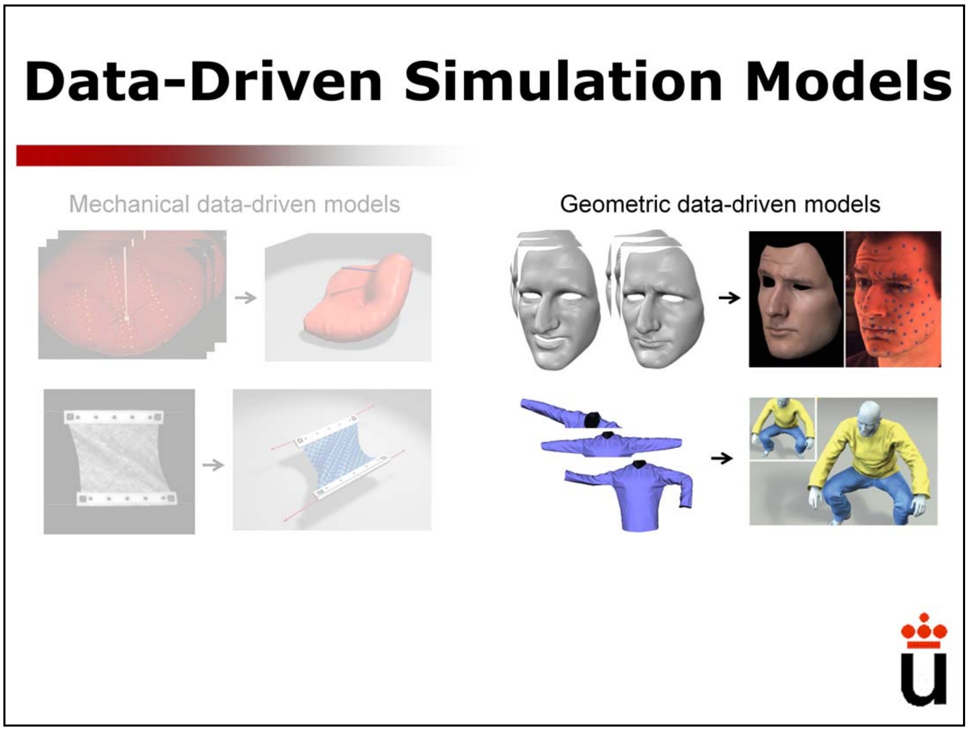


The other large project that we are involved in is an ERC Starting Grant called Animetrics: Measurement-Based Modeling and Animation of Complex Mechanical Phenomena.

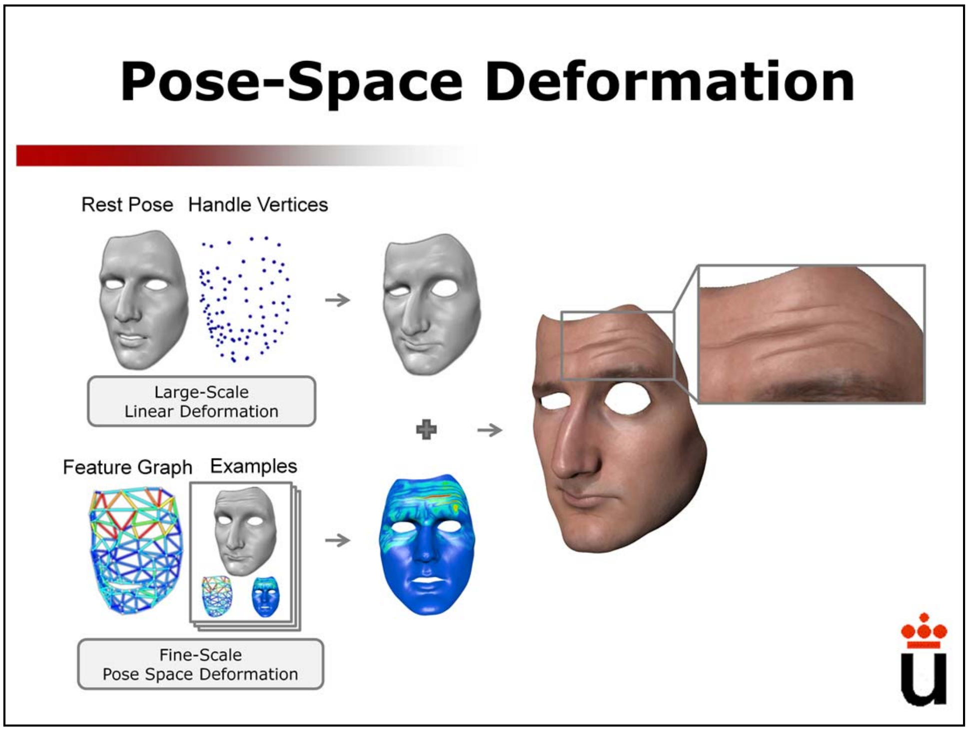
http://www.gmrv.es/layoutGMRV.php?name=Projects/Animetrics/prueba_en.html



Animetrics aims at modeling highly nonlinear phenomena, such as liquid turbulence, by leveraging two methodologies. One is to describe complex models through combinations of simple local models. The other is to capture massive example data to (i) decide what those local models look like, and (ii) decide how to combine them.



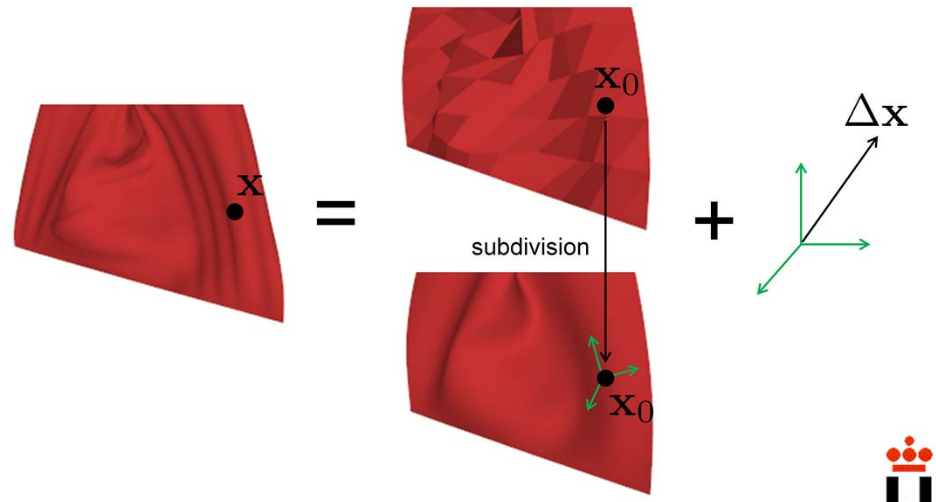
Animetrics considers two strategies to incorporate data: geometric models, where details are overlayed on low-resolution simulations simply as a function of geometric information, and mechanical models, where the mechanical properties are estimated from data.



Our first attempt at geometric models was to represent detailed facial animation using a multiscale model. Low resolution motion can be described efficiently as a linear model that depends on the positions of sparse markers. High-resolution detail, on the other hand, is added as a function of local low-resolution deformation using a data-driven approach.

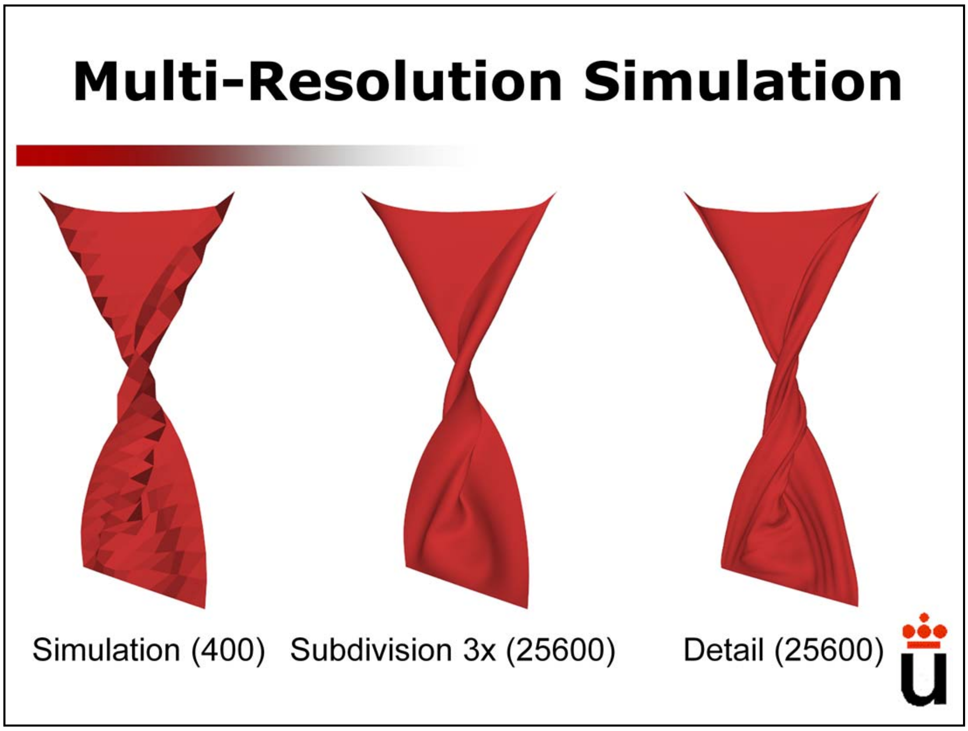
Bickel et al., ACM Symposium on Computer Animation 2008.
http://www.gmrv.es/Publications/2008/BLBOG08/

Representation of Geometry

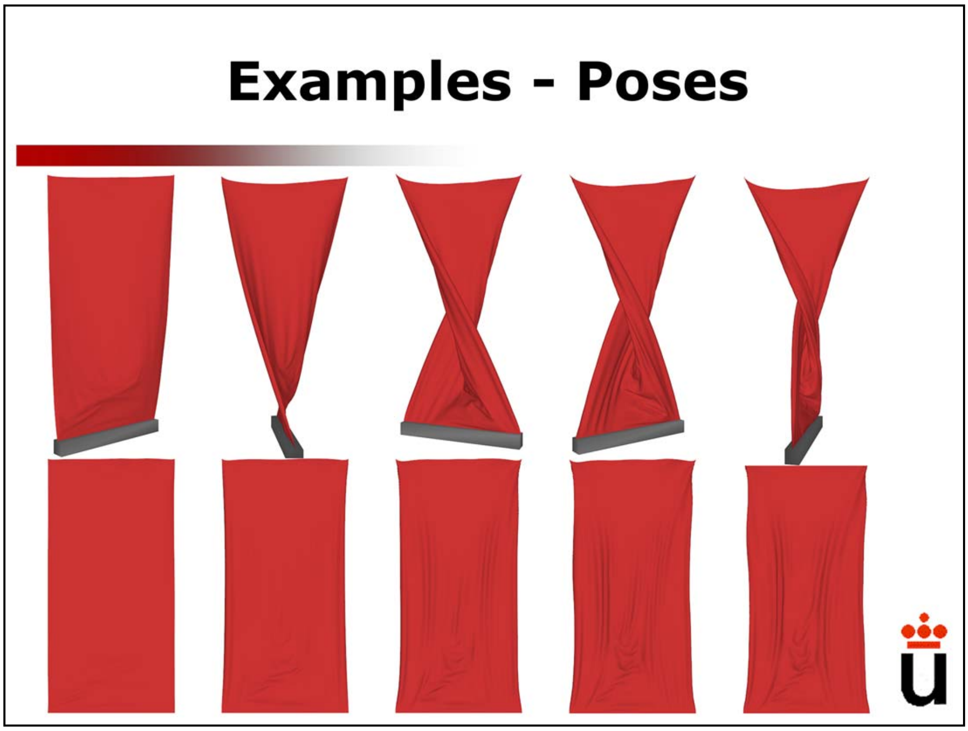


A similar idea is suited for cloth wrinkles. Here, we explain the complete data-driven model in more detail.

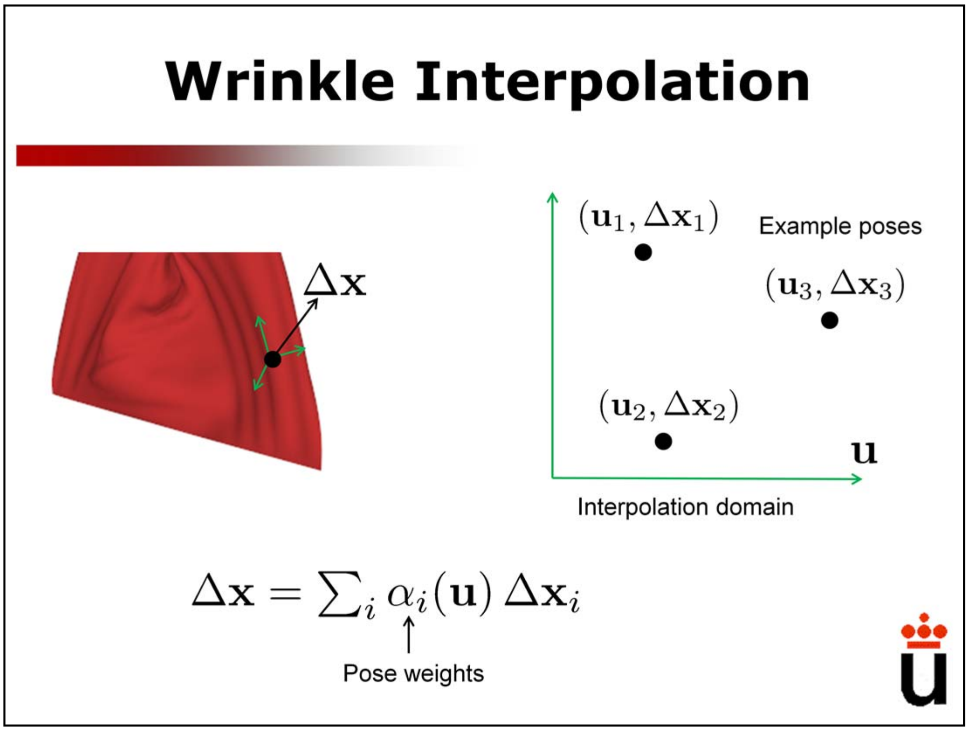
High-resolution cloth may be described as the addition of a smoothed low-resolution shape plus detail displacements expressed in a local reference frame.



Here is an example with a low-resolution cloth shape (400 triangles), a smooth subdivided version (25600 triangles but no surface detail), and the final enhanced surface.



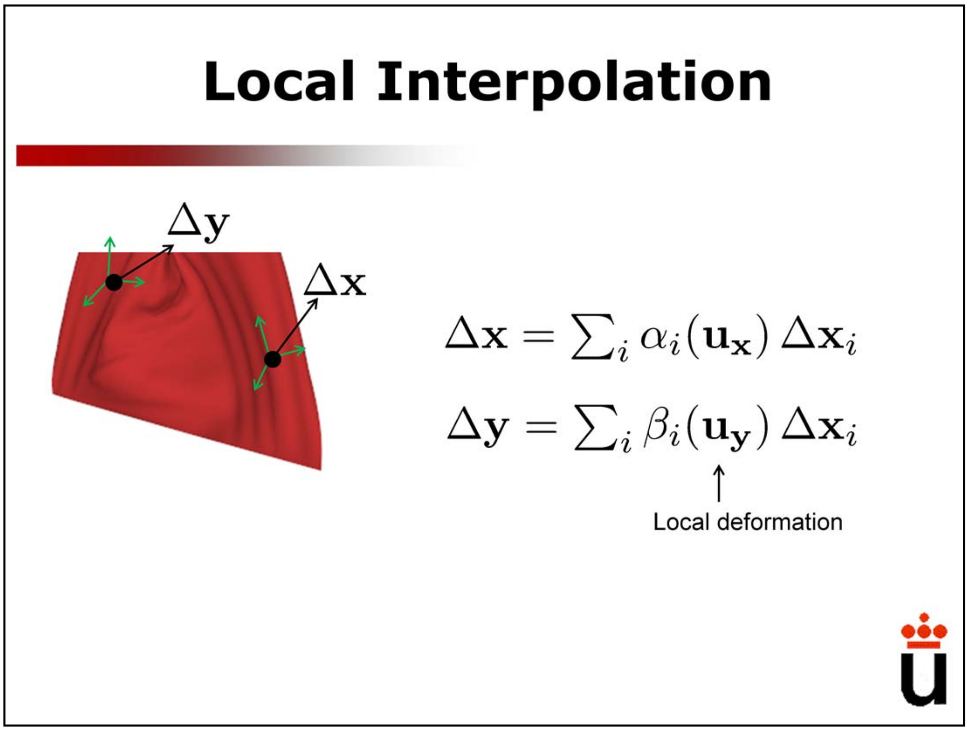
Detailed displacements can be modeled from examples. This slide shows 5 example poses and their corresponding displacement detail expressed in the local reference frame.



The computation of local displacements proceeds as follows.

We will define some interpolation domain, and we represent example poses as points in this domain. We choose as interpolation domain a measure of low-resolution strain (deformation).

Then, we compute detail displacements as a weighted combination of pose details. The alphas here represent pose weights.



Using global weights equal at all points in the cloth would require a huge number of example poses. To remedy this, we apply weighted pose-space deformation, which implies two changes:

-We use a local strain metric for each point.

-The weights are different for each point. In other words, we weight the examples differently at each point.

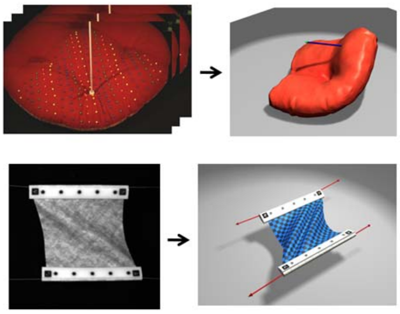
Results

An example of the data-driven geometric method applied to cloth.

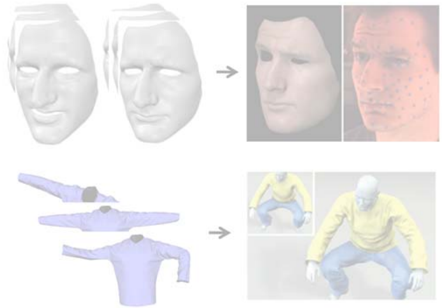
Zurdo et al. IEEE Trans. on Visualization and Computer Graphics 2013. http://www.gmrv.es/Publications/2013/ZBO13/

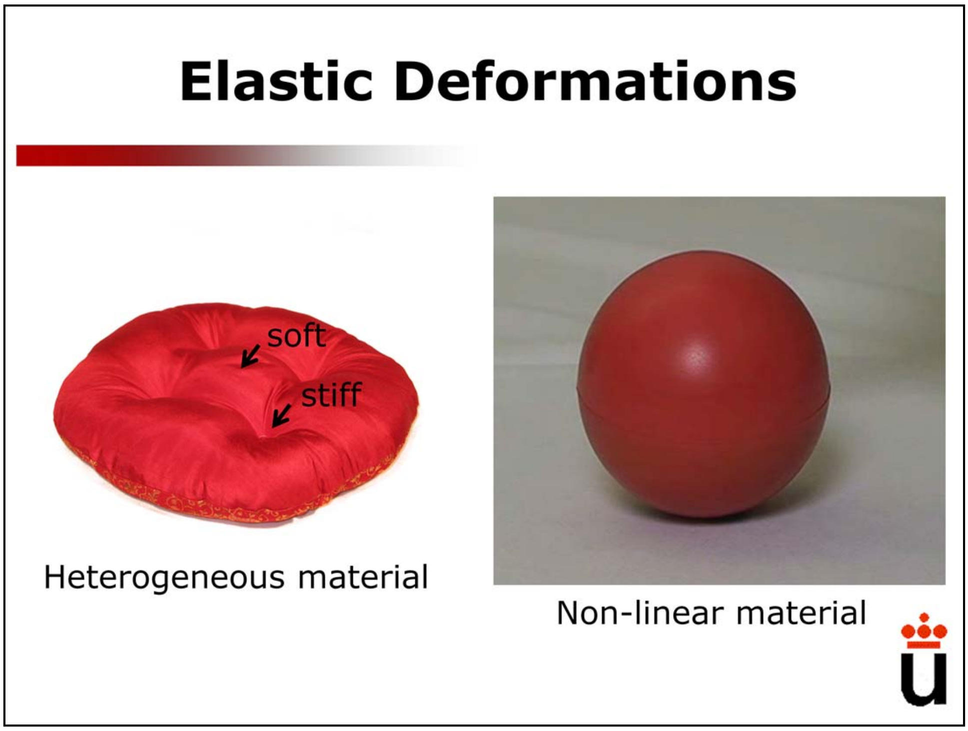
Data-Driven Simulation Models

Mechanical data-driven models



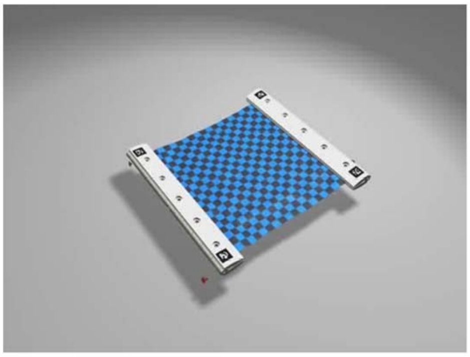
Geometric data-driven models

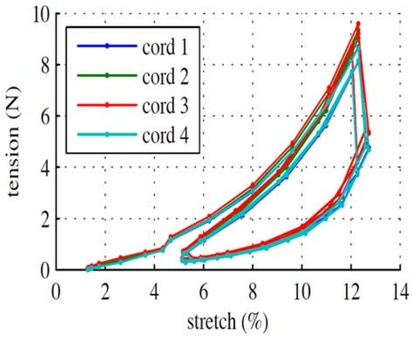




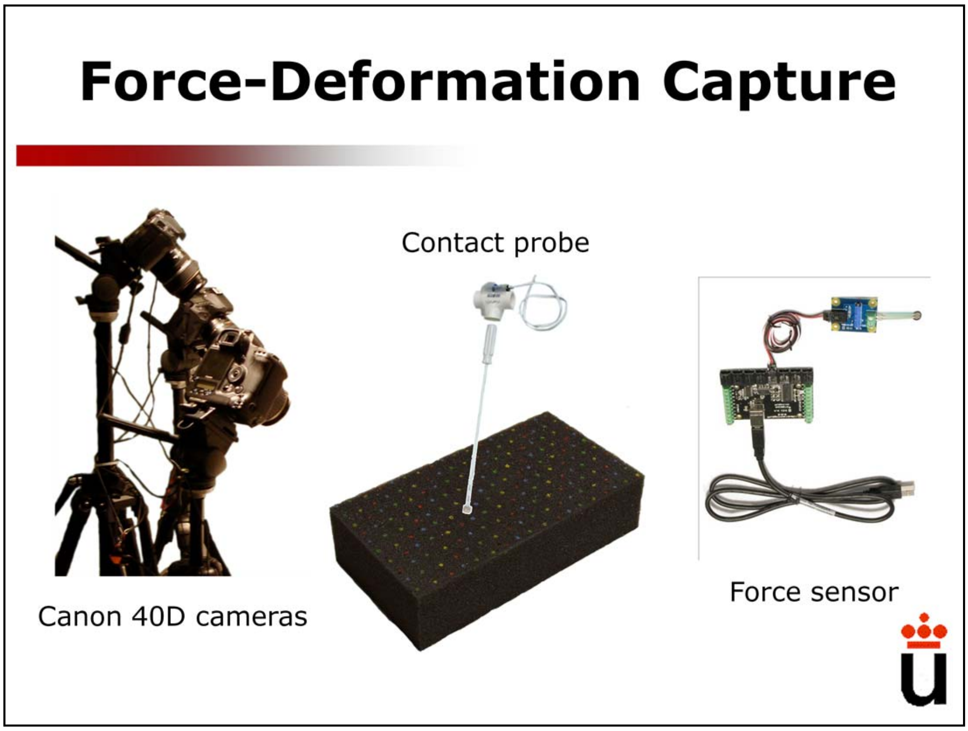
Real-world objects show many sources of complexity: stiffness nonlinearity, heterogeneity, anisotropy…

Elastic Deformations



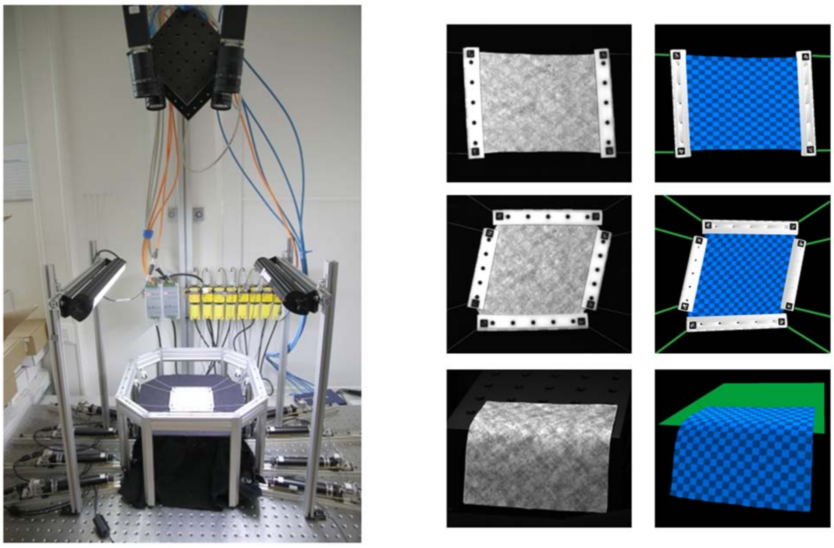


Here's an example of cloth, showing force-deformation curves when the cloth is pulled from 4 corners. Cloth exhibits large hysteresis, with the loading path (top) requiring up to 100% more force than the unloading path (bottom).

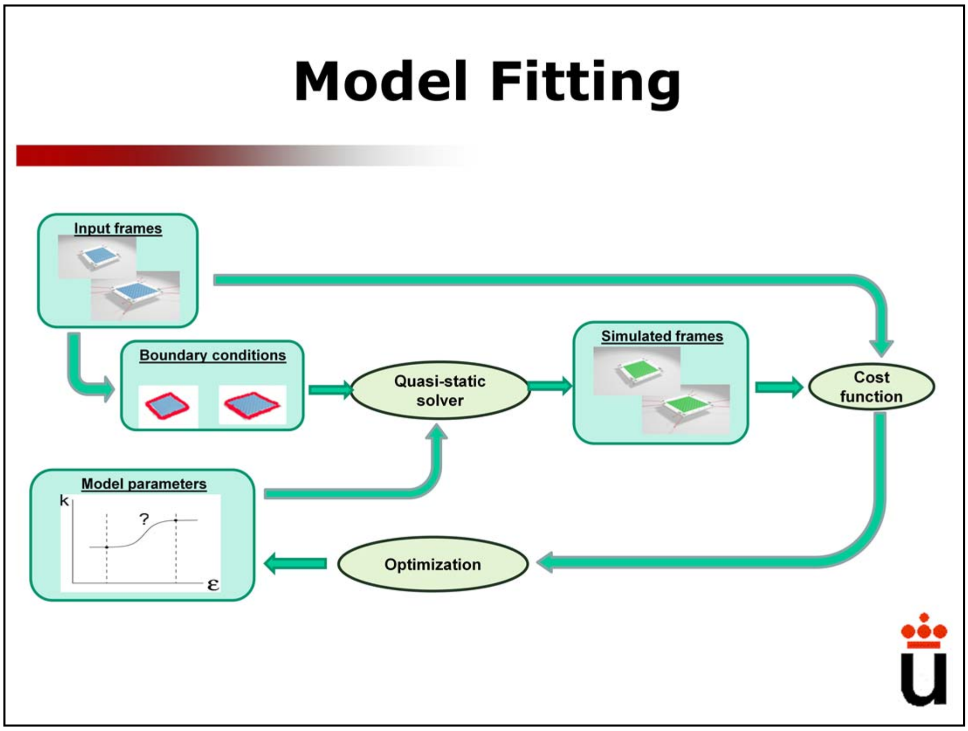


Our approach is to model complex mechanical behaviors using 3D force-deformation examples. Here is an example measurement setup consisting of computer-vision for 3D reconstruction, together with force sensors.

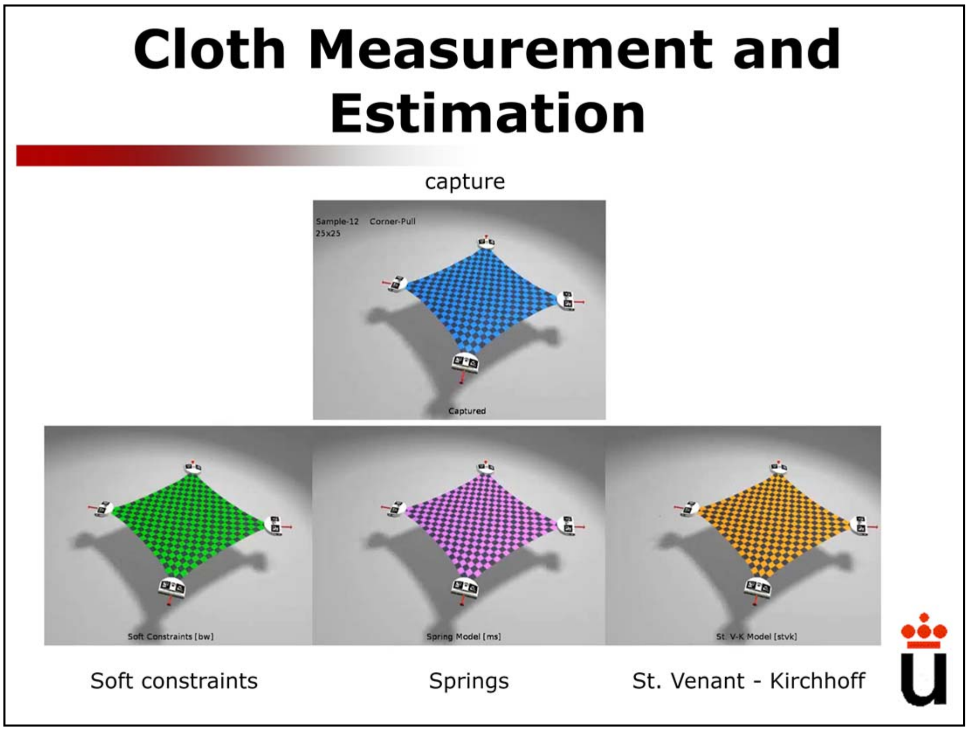
Cloth Capture



Here’s an example setup for cloth. The cloth sample (20cm x 20cm) is in the center, and it is pulled with controlled linear actuators through wires and pulleys. At the top there are 4 cameras for 3D reconstruction.



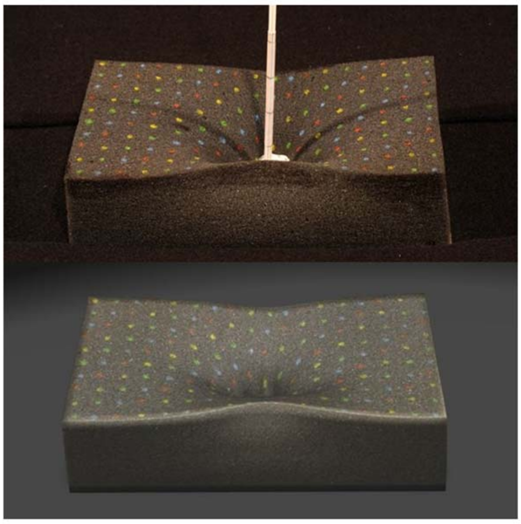
We describe the elastic behavior through an interpolation of linear models. To estimate model parameters, we follow an optimization strategy, such that the simulated behavior matches the observed one.



We have developed the full measurement and estimation framework, and compared estimations of several standard models with measurements.

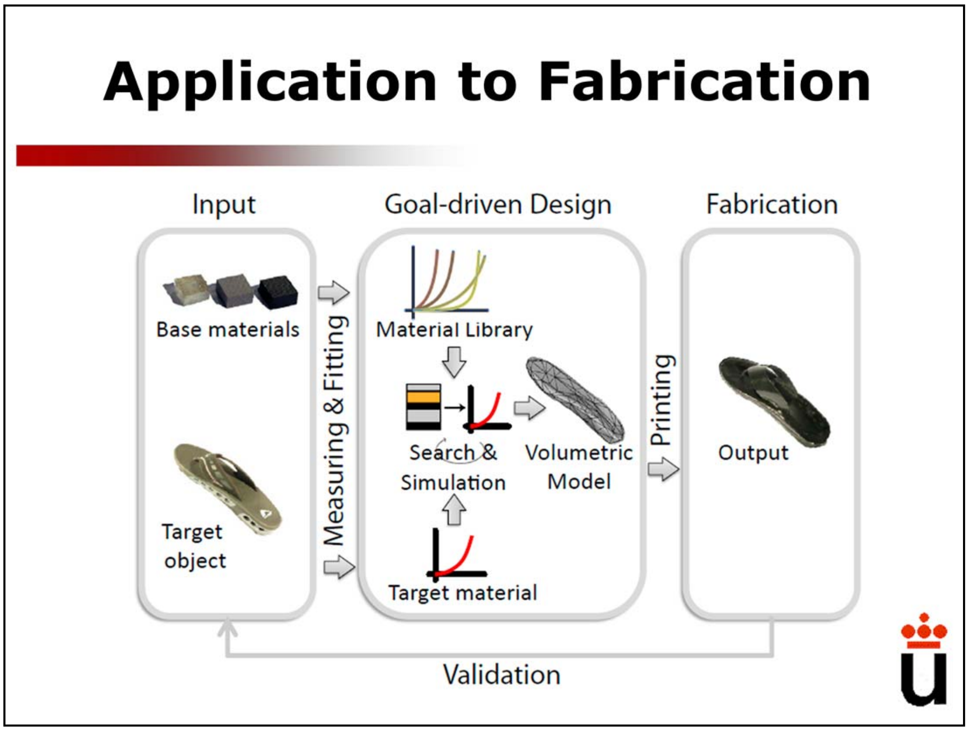
Miguel et al. Eurographics 2012.
http://www.gmrv.es/Publications/2012/MBTBMOM12/

Volumetric Tissue Measurement and Estimation



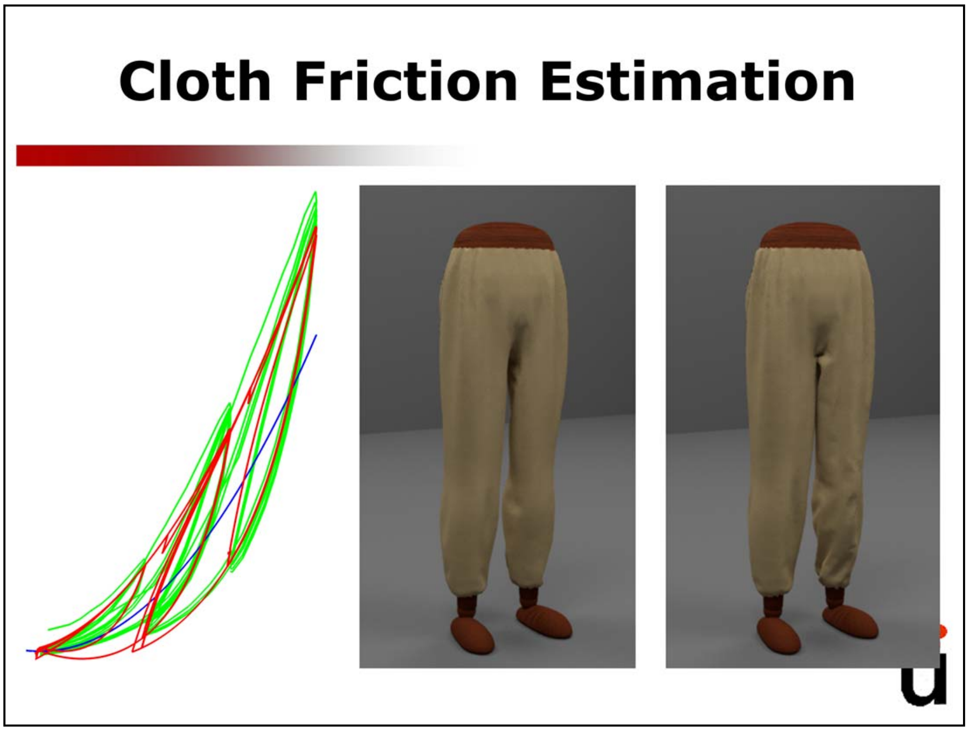
Similarly for solids, this image shows on top a real-world capture (not in the training set) with a simulated example on the bottom.

Bickel et al., ACM SIGGRAPH 2009. http://www.gmrv.es/Publications/2009/BBOMPG09/



An interesting application of data-driven models is fabrication-oriented design. In 3D printing technology it is possible to obtain a large range of materials by varying the combination of two basic materials at a small scale. In this project, we used data in two ways: to characterize the base materials and to specify the behavior of the desired object. The material composition of the object to be printed is computed through an inverse design optimization process.

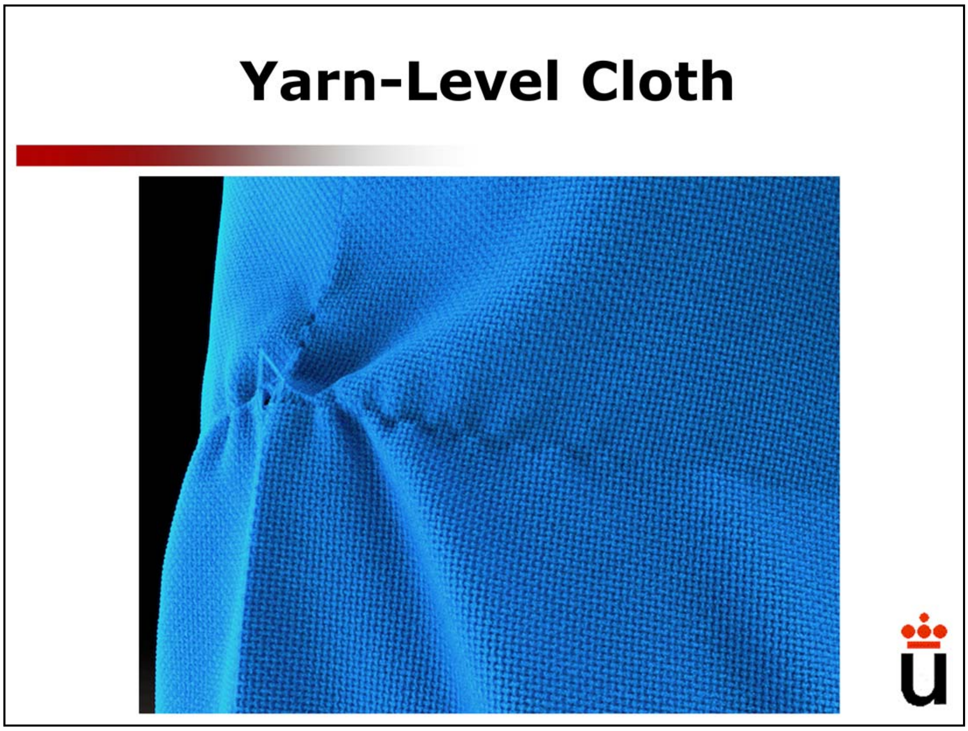
Bickel et al., ACM SIGGRAPH 2010. http://www.gmrv.es/Publications/2010/BBOLPGM10/



In addition to elasticity, we have also estimated friction behavior (hysteresis) from measurements. The plot shows measurements in green, a purely elastic estimation in blue, and frictional estimation in red.

The pants show, on the left, smooth deformation without friction, and on the right, wrinkles due to friction.

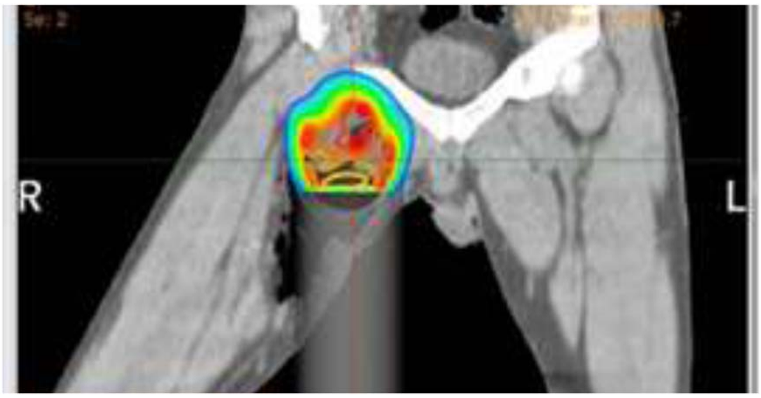
Miguel et al., ACM SIGGRAPH Asia 2013. http://www.gmrv.es/Publications/2013/MTBSTBMMO13/



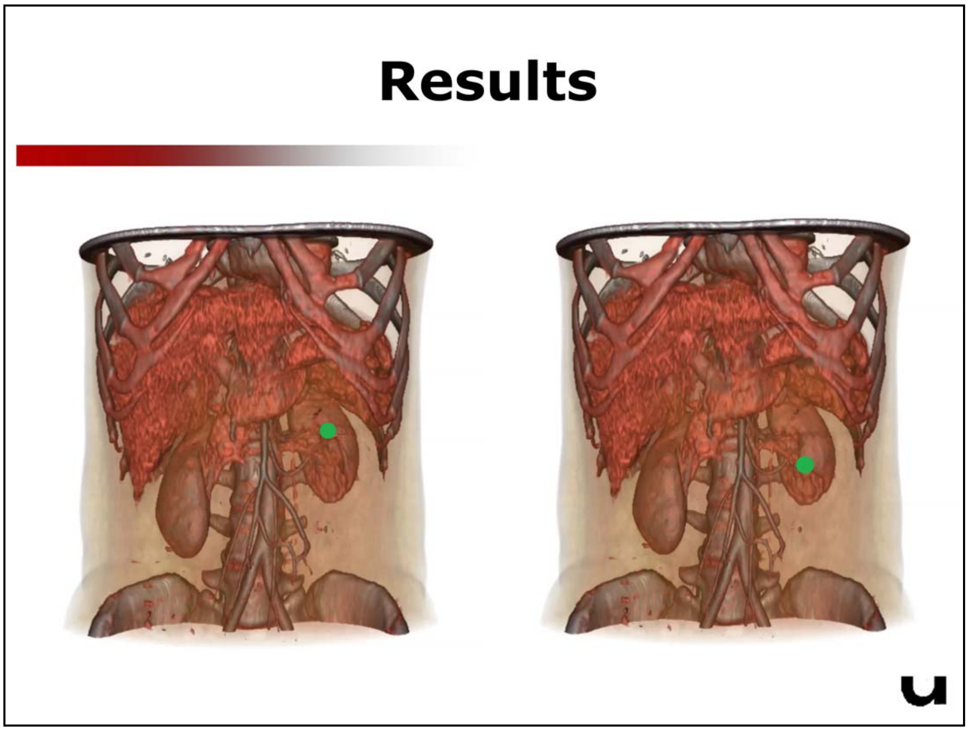
In a very recent work, we have applied our knowledge on cloth modeling and simulation to develop the first approach capable of simulating full woven garments at the yarn level.

Cirio et al., ACM SIGGRAPH Asia 2014. http://www.gmrv.es/Publications/2014/CLMO14/

XIORT (INNPACTO)



We also collaborate in an INNPACTO project, called XIORT, lead by the company GMV, and together with the Gregorio Marañón Hospital, the Polytechnic Univ. in Madrid, and the Carlos III Univ. The goal of this project is to develop techniques for planning intraoperative radiotherapy. Our task consists of providing innovative tools for interactive deformation of medical images.



The images show the ability to interact directly with the volumetric image and deform the underlying mechanical tissue. Our method is based on two technical contributions: massively parallel deformation of high-resolution volumetric images through tetrahedral rasterization, and a homogenization method for the efficient simulation of heterogeneous tissue.

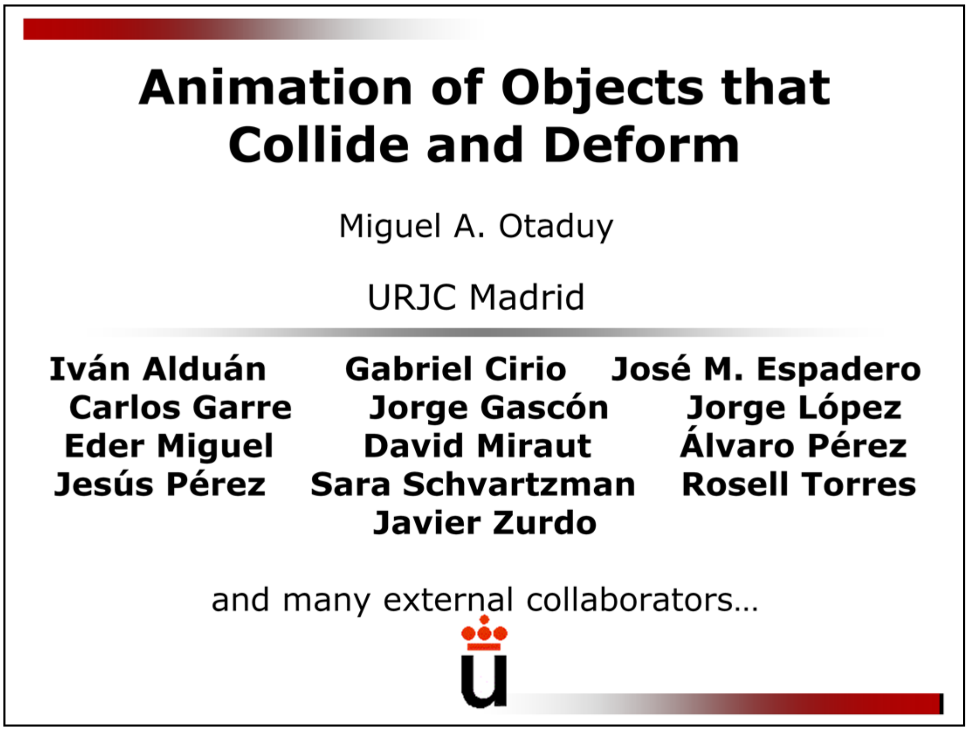
Gascón et al., ACM Symposium on Computer Animation 2013.
http://www.gmrv.es/Publications/2013/GEPTO13/

Torres et al., Intl. Symp. on Biomedical Simulation 2014.
http://www.gmrv.es/Publications/2014/TECO14/

Data-related challenges

- Choose the representation
- Design acquisition-estimation in tandem
- Model estimation algorithms

- General frameworks for data-driven models
- Exploit data and constraints for directable simulation



This work was possible thanks to the participation of many people. The list shows students and postdocs in the group since 2008.