Technical Report

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Experimental Validation of an Inextensible Cloth Model

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Abstract

In this technical report we present a framework for the empirical validation of a physical cloth model. First, we introduce the model to be validated and its parameters, next we explain how to obtain real world data of the motion of a textile and finally we show how to fit the model to the experimental data.

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1 Introduction

Robotic manipulation of textiles is a expanding research field nowadays with promising applications ranging from folding cloth to dressing a person. One of the main challenges faced is the high degree of deformation states that textiles can present. In contrast to rigid body manipulations where the dynamics of the manipulated object are very well understood, there is not one single model that can be considered best in term of describing the dynamics of real textiles. There are many different physical models (elasticity, springs, yarns, etc. see [3, 6]) but none has shown to be better than the other in all possible scenarios. In this report we aim to validate experimentally a model that assumes inextensibility of the garment at hand. This greatly simplifies the validation, because it reduces the number of parameters of the model greatly.

This report is structured as follows: first, we give a brief introduction of the model we will be validating, highlighting its physical and simulation parameters. The first are the ones we will be interested in fitting (they are the density, stiffness and damping of the textile) and the second are present because of the discretization and implementation of the model, but they do not have a physical meaning (e.g. time step and mesh resolution).

Next, we explain how to capture real world data. The main idea is to use a depth camera to record the real motion of a garment. Then, de-noise, interpolate and mesh the resulting point-cloud, so that we end up with the spatial trajectory of the nodes of a meshed polyhedron. To our knowledge we are the first to attempt a dynamic validation of a cloth model, in contrast to static approaches [8]. In order to keep things simple, we focus on a rectangular piece of cloth made of cotton of dimensions 30×40 cm and weight 25 g. This is the typical material used for formal shirts.

Finally, we find the parameters of the theoretical model that best approximate the motion of the polyhedron using a least squares approximation and a search algorithm. For the purposes of keeping this report short we only include the analysis of one type of motion: a going forward and backwards oscillation (see Figure 1), leaving a more in depth study for future work.

2 Cloth model

As mentioned in the introduction, the garment to be used for the experiment is a rectangular piece of cloth, this simplifies the meshing procedure of the point-cloud later and solves a possible occlusion problem of the depth camera. Being the garment rectangular, the natural discretization of it is in quadrilaterals (see Figure 1). Therefore, in order to know the position of the textile we only need the spatial location of the vertices of the mesh.

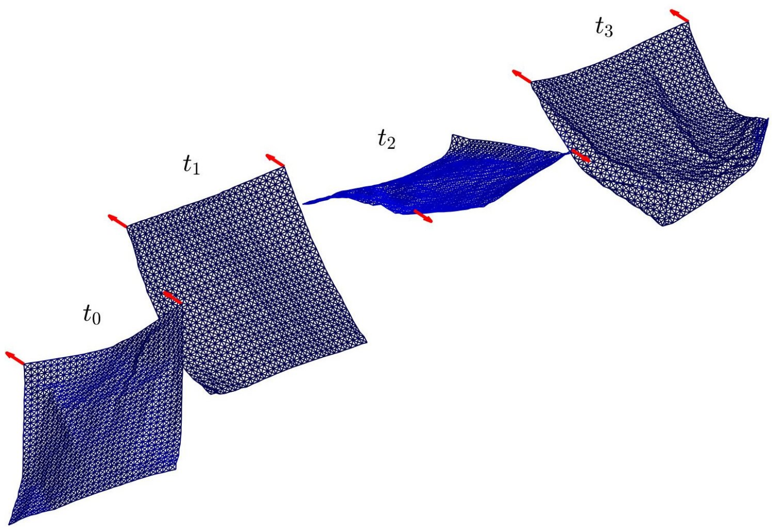

Figure 1: Numerical simulation of the shaking motion we will be using with the real textile. Note how the textile is discretized into a polyhedron.

Letting $\boldsymbol{\varphi}(t) \in \mathbb{R}^{3N}$ be the position of the N nodes of the mesh, the following ordinary differential equation system (see e.g. [4]) describes the motion of the blanket:

$$\begin{cases} \rho \mathbf{M}\ddot{\boldsymbol{\varphi}} = \mathbf{F}_g - \theta \cdot \mathbf{K}\boldsymbol{\varphi} - \mathbf{D}\dot{\boldsymbol{\varphi}} - \nabla \mathbf{C}(\boldsymbol{\varphi})^\intercal \boldsymbol{\lambda} \\ \mathbf{C}(\boldsymbol{\varphi}) = 0 \end{cases} \tag{1}$$

where

1. $\rho > 0$ is the density of the cloth, $\mathbf{M}$ is the augmented mass matrix [2] and $\mathbf{F}_g$ is the force of gravity.

2. $\mathbf{K}$ is the stiffness matrix (we are using the isometric bending model described in [1]) and hence θ is a stiffness parameter.

3. the matrix $\mathbf{D} = \alpha \mathbf{M} + \beta \mathbf{K}$ is called Rayleigh damping [9]: α and β are positive damping parameters.

4. $\boldsymbol{\lambda}(t)$ are the Lagrange multipliers [7] ensuring inextensibility and $\mathbf{C}$ are the inextensibility constraints.

Note how inextensibility reduces greatly the number of physical parameters of the model (we do not have shearing or stretching parameters and their respective dampings), hence we only need to find θ, α, β because ρ can be measured. System (1) is integrated numerically using an implicit Euler scheme as outlined in [4].

3 Camera data

A depth camera (see Figure 2) is used to record the motion of the cotton garment being shaken by moving the upper two corners along horizontal rails following a synchronized oscillatory trajectory (see Figure 1). The oscillation occurs at a fixed height and it is made by a robotic arm in a controlled manner in such a way that occlusions do not occur.

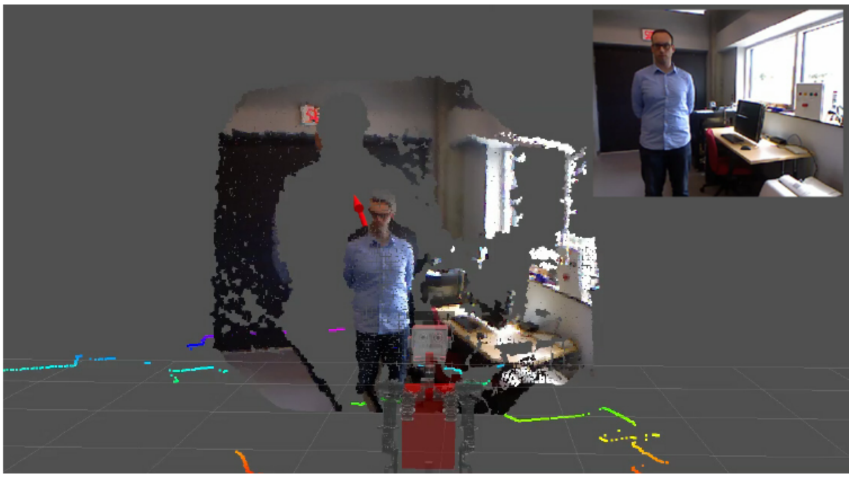

Figure 2: Point cloud obtained using a depth camera (left) and flat image (right). Note that the camera only gets the depth of the objects visible to it, all the rest is occluded (e.g. part of the blackboard behind the man).

Then, for each recorded frame we filter background objects using a simple depth plane. On top of that, outliers points are removed by distance, and since our garment is of a uniform color (blue) we apply a color filter to remove further noise. Finally, each point-cloud is meshed (see Figure 3) using the algorithm described in [5] and interpolated so that we have the nodes of the polyhedron at equally spaced time steps.

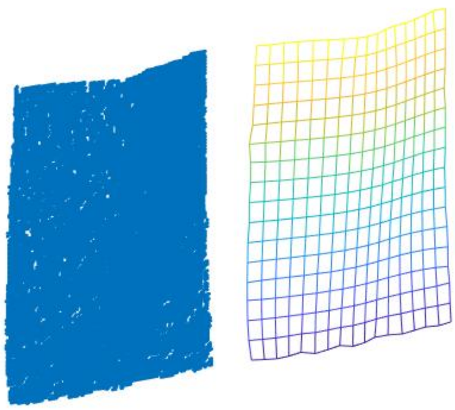

Figure 3: Quadrilateral meshing (right) of one of the frames of the filtered and de-noised point-cloud (left).

4 Parameter fitting

In this section we explain how to find the main parameters of the model. As mentioned before the density can be measured ($\rho = 0.025/(0.3 \times 0.4) \approx 0.2$) and thus will not be fitted. Hence we are left with 3 parameters: the stiffness θ, the high oscillations damping α and the low oscillations damping β. In the previous section we explained how to construct a sequence of positions of the nodes of the real blanket $\{\boldsymbol{\phi}^0, \boldsymbol{\phi}^1, \ldots, \boldsymbol{\phi}^n\}$. Integrating numerically equations (1) using the same oscillatory motion for the two upper corners, we obtain a sequence $\{\boldsymbol{\varphi}^0(\theta, \alpha, \beta), \boldsymbol{\varphi}^1(\theta, \alpha, \beta), \ldots, \boldsymbol{\varphi}^n(\theta, \alpha, \beta)\}$ (where $\boldsymbol{\varphi}^0 = \boldsymbol{\phi}^0$) for each given value of the physical parameters. Therefore a natural metric is:

$$L(\theta, \alpha, \beta) = \sum_{i=1}^{n} ||\boldsymbol{\varphi}^i(\theta, \alpha, \beta) - \boldsymbol{\phi}^i||^2 \tag{2}$$

Finally, we minimize L using a derivative free algorithm and find the optimal values of θ, α, β. For our cotton example, using a 9×9 mesh, we obtain that θ and β are set to 0 by the algorithm and the only significant parameter is $\alpha = 1.5$.

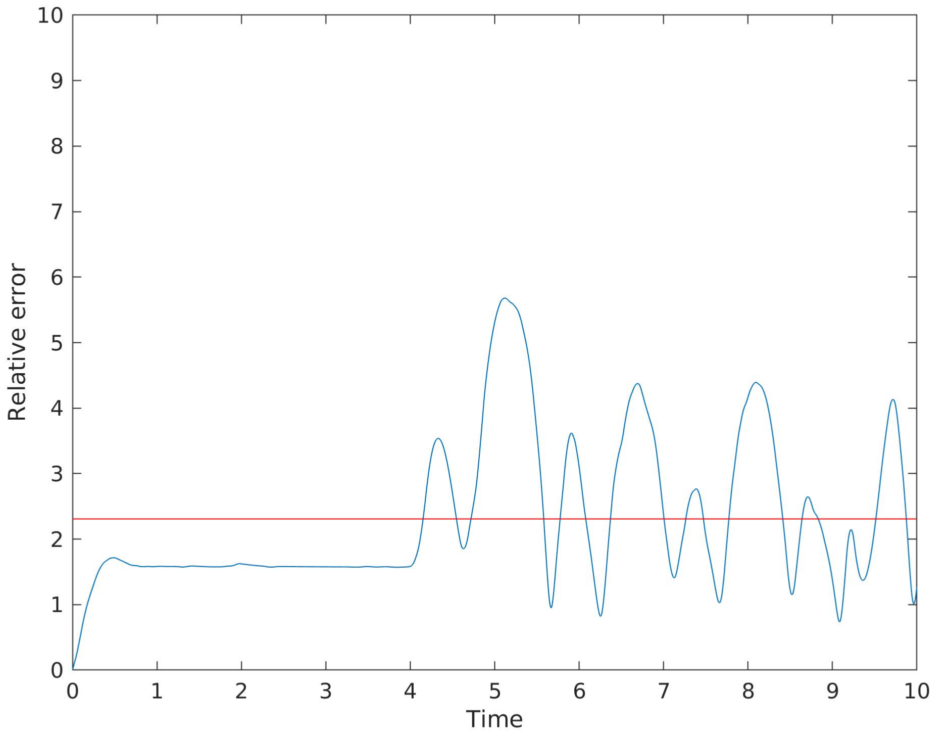

Figure 4: Relative error (%) of the position of the simulated blanket vs. the real one.

For plotting purposes is better to study a time dependent relative error instead of the global error previously defined. Hence we write

$$e_i(\theta, \alpha, \beta) = 100 \times \sqrt{\frac{||\boldsymbol{\varphi}^i(\theta, \alpha, \beta) - \boldsymbol{\phi}^i||^2}{||\boldsymbol{\phi}^i||^2}}. \tag{3}$$

Notice in Figure 4 how this error is very low (always under 6%) and with mean around 2%.

5 Conclusions

In this technical report we have presented and illustrated a framework for the empirical validation of a cloth model. The results are very promising for a cotton blanket and an oscillatory motion with very low relative errors (under 6%). Moreover, only one physical parameter is needed to achieve this level of precision. To our knowledge we are the first to attempt a dynamic calibration of a theoretical cloth model (all past research has focused on static calibrations). Further investigation is necessary using different types of fabrics and other dynamic motions. Furthermore, factors that may introduce error in the fitting procedure not addressed in this report are: the calibration of the depth camera with respect to the cloth and the aerodynamics of the textile.

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