Does loose fitting matter? Predicting sensor performance in smart garments.

Holger Harms
Wearable Computing Lab,
Electronics Laboratory,
ETH Zurich
harms@ieee.org

Oliver Amft
ACTLab,
Signal Processing Systems,
TU Einhoven
amft@ieee.org

Gerhard Tröster
Wearable Computing Lab,
Electronics Laboratory,
ETH Zurich
troester@ife.ee.ethz.ch

ABSTRACT

Smart sensing garments can extend the functionality of clothing beyond aesthetic and protective purposes. In contrast to skin-mounted sensors, garment-embedded sensor performance depends on fitting. In this work, we present a modeling and simulation approach to predict sensor performance in garments. We implemented a state-of-the-art particle-based model of fabrics to simulate the topology and drape of the garment. Based on the simulation, we introduce a method to extract and visualize maps for garment-embedded sensor performance metrics. We present performance maps for three basic modalities pertained to orientation, skin contact, and strain. Design parameters as garment fitting and material, and body proportion are analyzed regarding position specific sensor performance. To evaluate our model, we compared simulations to participant study data, confirming that our approach is suitable to plan sensor positioning and garment design before implementing garment prototypes.

Categories and Subject Descriptors

I.3.8 [**Computer Graphics**]: Simulation and Modeling—*Applications*

General Terms

Algorithms

1. INTRODUCTION

Sensing and processing functionality in clothing, as they are used in current sports and rehabilitation solutions, confirm that fabrics are a vital substrate for wearable systems. By covering large sections of the body surface, *sensing garments* become the essential basis for distributed monitoring of physiological signals and body motion in everyday life. While applicable for continuous use, sensing garments need to comply with wearers' comfort and fitting requirements [5], which often hamper measurement performance. Previous studies confirmed that tight-fitting cloths are frequently perceived uncomfortable while most sensors and applications benefit from a close textile-body coupling. For example, the suitability of an garment-embedded acceleration sensor to recognize body postures can diminish, if the garment is "wide" and thus develops wrinkles.

Recent research prototypes based on non-tight fitting sensing garments showed that postures and activities could still be recognized at reduced accuracy using orientation sensors [3]. However, for non-tight garments selecting appropriate sensor positions is essential. So far, sensor placement is often performed empirically and by expert opinion, which may not be optimal, or generalize to a population.

Garment fitting simulations have the potential to support this critical design phase [6]. However, commercial prototyping tools for simulation of garment drape were insufficient to derive garment-embedded sensor performance maps. The simulation software that we evaluated relied on models that were optimized for fast simulations of garment drape at the expense of an approximated accuracy. While simulations allow designer for qualitative assessments of the aesthetics and developed drape, we aim for quantitative measures. Hence, we implemented a physical particle-based model of fabrics as proposed in state-of-the-art literature. Like in conventional prototyping tools, our model allowed us to control basic design parameters, including body posture and proportion, garment material, and fitting. In addition, we customized the model to control particular parameter including the location-dependent mass and rigidity of attached electronics and cables.

Based on the garment simulation, we propose an approach to quantify and illustrate sensor performance maps for sensor modalities that are predominant in wearable systems. From simulated fabrics, we derived (1) internal strain, (2) relative orientation of the garment to the body surface and (3) distance to the body surface. These maps show garment regions, where low drape-induced sensing errors can be expected, thus, sensors shall be placed.

As a complete validation of various modalities is beyond the scope of this paper, we focused on an evaluation regarding orientation sensor performance. We compared our results to previously published participant study data and confirm that the simulation is realistic.

BODYNETS 2012, September 24-26, Oslo, Norway

DOI 10.4108/icst.bodynets.2012.249968

2. SIMULATION APPROACH

Our framework comprises two modules to investigate garment-embedded sensor performance. Figure 1 illustrates the modules and their interfaces. In the first module we utilized a particle-based model of fabrics adapted from computer graphics research to simulate garments. The model allowed us to simulate the garment topology (drape) at a human body model based on physical laws and custom design parameters.

In the second module, we utilized the simulated garment topology in combination with a static human body model to estimate performance maps for garment-embedded sensors. The output of this module is a location-specific performance map of a selected sensor modality. We addressed three types of basic sensor modalities whose sensitivity or accuracy rely on either (1) internal strain of tight fitting garments, (2) body-garment distance, or (3) angular deviation between the body and garment surface in non-tight fitting garments.

The entire framework was implemented in *C++*, for the visualization of the garment we utilized the *Visualization Toolkit* (VTK) library. In the following subsections both modules and relevant aspects are detailed.

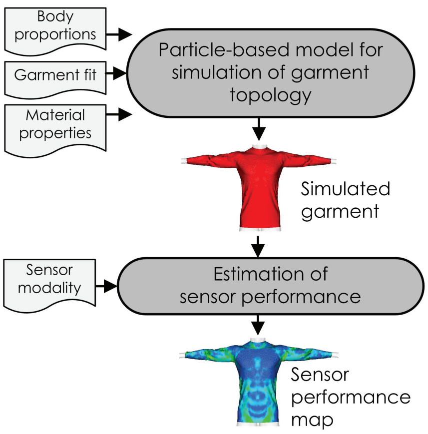


Figure 1: Modeling and simulation modules. The particle-based model of fabrics is used to simulate the garment at a human body. Simulation results are used to estimate garment-embedded sensor performance maps.

2.1 Model for garment simulation

We utilized a particle-based model of fabrics to describe the garment topology at a human body model. Figure 2 illustrates our overall approach. Just like in real clothing, a simulated garment comprises independent fabric patches that are sewn together. Each two fabric patches formed left and right sleeve and two patches were placed at front and back of the torso. Individual patches are represented by irregular triangle meshes of interconnected particles that form edges of the triangles. Each particle has attributes associated with it, including mass, position, velocity, and forces acting on the particle. The force acting on an individual particle i consist of superimposed internal and external force components.

Forces acting inside each fabric are composed of in-plane

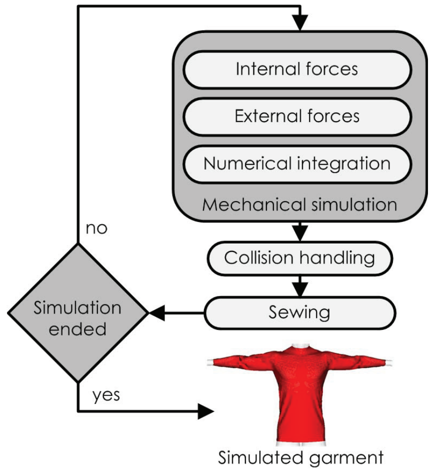


Figure 2: Schematic of the particle-based model of fabrics.

forces $\mathbf{F}_i^I$ and out-of-plane forces $\mathbf{F}_i^O$. In-plane forces $\mathbf{F}_i^I$ define the reaction of the fabric to intrinsic strain and cause elongation. In this work, we implemented the in-plane force modeling approach as presented in [8], which achieved an estimation error below 1% for strain up to 50%. Out-of-plane forces $\mathbf{F}_i^O$ define the corresponding garment behavior when the fabric is bent. Here, we implemented an approach of [1] that considers physical parameter as bending rigidity Γ_i.

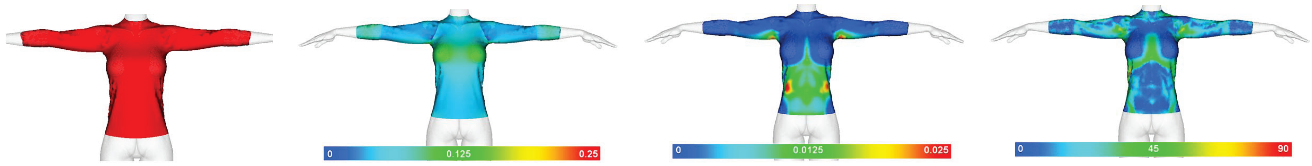
External forces comprise all effects that influence particles but are not based on in-plane forces or out-of-plane forces. We considered gravity $\mathbf{F}_i^G$ and mechanical damping $\mathbf{F}_i^D$. Gravity is incorporated by adding the vector $\mathbf{F}_i^G$ onto each individual particle i according to $\mathbf{F}_i^G = m_i \cdot \mathbf{G}$, where m_i denotes the particle-specific mass and $\mathbf{G}$ is a vector of gravity components ($G = (0, 0, -9.8)m/s^2$).

The particle mass m_i and bending rigidity Γ_i were exploited to model the mass and stiffness of sensors, electronics, and cables at specific regions on the garment.

The resulting force acting on a particle $\mathbf{F}_i$ is composed of elasticity, bending, gravity, and damping effects, according to $\mathbf{F}_i = \mathbf{F}_i^I + \mathbf{F}_i^O + \mathbf{F}_i^G + \mathbf{F}_i^D$. Following Newton's second law $\mathbf{F}_i = m_i \cdot \ddot{\mathbf{x}}$, the acceleration of each particle $\ddot{\mathbf{x}}$ was derived by normalizing with the particle mass m_i. Acceleration was subsequently integrated over a discrete time step dt to compute velocity $\dot{\mathbf{x}}$, and with a second integration to calculate the particle position $\mathbf{x}$. We used a first order semi-implicit Euler integrator to compute the next time step, following $\mathbf{x}_{t+dt} = \mathbf{x}_t + \dot{\mathbf{x}}_{t+dt} \cdot dt$ and $\dot{\mathbf{x}}_{t+dt} = \dot{\mathbf{x}}_t + \frac{1}{m} \cdot \mathbf{F}(\mathbf{x}_t, \dot{\mathbf{x}}_t) \cdot dt$ for velocity and position respectively.

By repeating the integration step, particle positions were iteratively modified. During iterations, fabric patches align at the human body model and converge to a shape where forces between particles are in an equilibrium state.

During integration, the particle movement was constrained to avoid collisions according the geometric collision detection approach presented in [4].



(a) Reference garment (b) Vertical strain (c) Body-garment distance (d) Angular deviation

Figure 3: Reference and sensor performance maps (front view). (a): Reference garment at a female body model. (b): Dimensionless vertical strain (ϵ), e.g. for strain sensors. (c): Body-garment distance in meter, e.g. for electrodes. (d): Angular Deviation (AD) between garment and body surfaces in degree, e.g. for orientation sensors.

Design parameters of the particle-based model. Our modeling approach allowed us to control various important parameters that have direct influence on the final sensor garment performance. The following paragraphs indicate how the body proportions of the wearer, the garment fit, and material properties of the garment can be varied by designers during the development process.

Body proportions: A variation of the body proportions allows the designer to estimate the sensor performance at specific locations for a spectrum of user, before a garment is implemented. Body proportions, gender, and posture of the wearer are defined by a static mesh of the human body that is input to the garment simulation. We used the Poser software [7] to morph parametrized human body models, and subsequently import the result into our framework.

Garment fit: It might be of interest for the garment designer to achieve a sufficient compromise between required sensor performance and wearing comfort. Garment fitting was controlled via the Body Garment Mobility BGM, defined by $BGM = \frac{D_{Garment}}{D_{Segment}} - 1$. BGM describes the dimensionless ratio of garment circumference $D_{garment}$ and body segment circumference $D_{segment}$ at any cross section of the segment. To denote BGM, we assumed a tube-like shape of a body segment (torso and limbs). For evaluations in this work, we initially generated a tight fitting garment with ($BGM \sim 0$). By scaling torso and sleeves' dimensions, we manipulated the patch circumference and thus approximated BGM.

Material properties: Important material properties influencing drape development include mass density and bending rigidity (Γ). Bending rigidity is modeled as out-of-plane force and defines the counteracting force if a garment is bent. Material constants considered for in-plane forces are the Young's Modulus (E), and Poisson ratio (ν).

2.2 Model for sensor performance

In our second module, the simulated garment topology was exploited to estimate garment-embedded sensor performance. In this work, we introduce sensor performance maps to illustrate garment-induced effects on sensors that are caused by a loose fit (see Figure 3(a)). Specifically, the effects on the following three basic sensor modalities were investigated

Internal strain: Tight-fitting garments with integrated strain-sensitive materials or fibers have proven to reliably monitor body posture and respiration. While garments must be sufficiently tight to follow the body surface and provide meaningful measurements, tight fitting should not hamper movements and the wearer's breathing. In our approach, strain was extracted from simulated fabrics by comparing initial and actual distances between particles in the fabric meshes. Figure 3(b) shows an example of our reference garment using color-coded vertical strain. While strain was distributed across the garment, increased strain could be observed in the upper torso region and at sewing paths, which corresponded to our expectations.

Body-garment distance: Various garment-attached sensors or electrodes require close contact to the skin to reliably acquire physiological data. Quantifying the body-garment distance can support the designer to identify garment regions, where sensors achieve close skin contact, hence potential sensor performance is high. The body-garment distance denotes the average distance between nearest fabric and body model particle. Figure 3(c) depicts the color-coded body-garment distance.

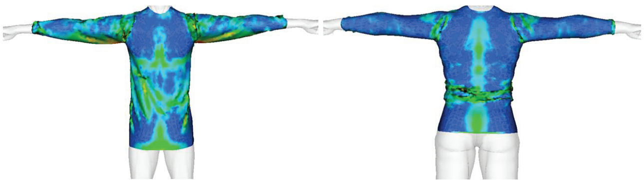
Angular deviation: Angular deviation (AD) describes the isotropic angle between body and garment surfaces. The sensor performance is potentially high for small AD, as changes in the garment orientation relative to the skin deteriorates measurement accuracy, e.g. of orientation sensors. Here, AD was calculated by comparing normal vectors of the garment (triangle mesh) surface with the underlying body model. Figure 3(d) shows the color-coded AD for our reference garment.

3. PREDICTION OF STUDY RESULTS

To evaluate our overall modeling approach, we investigated the effect of body proportions on fitting and orientation sensor performance. In an earlier study with children we observed that body proportions can significantly influence the accuracy of garment-based body posture measurements [2]. Here, we utilized sensor performance maps of angular deviation and compared simulation results to study observations.

Study design and results. In the study with 21 children aged between 7 and 14 years, we investigated the applicability of garments with embedded acceleration sensors to monitor the sagittal back inclination [2]. Four acceleration sensors were fixed on defined positions at the back of a long-sleeve shirt. Subsequently, garment-embedded sensor accuracy was evaluated and compared to a vision-based reference system. In the course of the study, children adopted different back and head positions. Here, we consider the drape

(a) Actual sensing garment in study



(b) Simulated sensor performance maps for angular deviation

Figure 4: Study and simulated drape (back view).

effect in a upright standing position. Figure 4(a) depicts two drape examples from children of different body proportions wearing the same garment with a size of 142 cm.

Simulation settings. For visual evaluation, we scaled the fabric patches of a simulated long-sleeve shirt to the dimensions of the sensing garment used in this study. Moreover, we configured circumferences of the children's chest and waist regions and produced two body models, thus approximating the BGM metric to the actual values. Material properties were set to cotton (bending rigidity $\Gamma = 4.41\,N/m$, mass density $W = 0.12\,kg/m^2$, Young's modulus $E = 6.65\,GPa$, Poisson coefficient $\nu = 0.15$). The resulting sensor performance maps for the garment back region are depicted in Figure 4(b).

Comparison of study and simulation. Visual evaluation of simulation and study drape revealed congruent position and alignment of wrinkles for the body proportions considered. In the left example participant of Figure 4(b), we observed vertical drape in middle and lower back regions, due to high BGM. In contrast, the garment showed horizontal drape for the right participant in Figure 4(b). The tight fit (small BGM) in the hip region compressed the garment and resulted in wrinkles.

In both examples, a sensor placement in middle and lower back regions along the spine could result in orientation errors due to garment-induced deflections. Figure 4 indicates low drape and angular deviations for sensors placed at the upper back and scapula. This simulation result was confirmed by our study, where for all children the scapula sensor showed the smallest garment-induced sensor orientation error. The sensor at mid back region showed marginally smaller accuracy, while sensors placed at lower and upper back were considerably deflected by wrinkles. The discrepancy between simulation and study results for sensor at the upper back could be explained from long hair of participants, that sporadically shifted the sensor.

4. CONCLUSION

The particle-based model of fabrics used in this work showed that authentic simulations of garments can be achieved. Corresponding to modalities prevalent in sensing garment designs, we derived performance measures that can be conveniently inspected through visual performance maps. Internal strain among particles was used for strain sensing, body-garment distance for skin-coupled sensors or electrodes, and angular deviation between garment and body for orientation sensors. Our evaluation of orientation sensor performance between simulated drape and children of the garment sensing study confirmed that realistic results can be derived. We expect that our simulation framework supports garment designers to determine sensor placement before prototyping garments. Our garment modeling and simulation approach is not limited to orientation sensors only. Thus, the simulation may shorten design cycles and study iterations for various sensing garment applications. Effects of design decisions could be explored before actually implementing garment prototypes. Further work is needed to evaluate material properties and multi-layer garments, including aspects such as friction. Also, the introduction of dynamics, as present in movements, could add further insights into garment fitting.

5. REFERENCES

[1] F. Cordier and N. Magnenat-Thalmann. Real-time animation of dressed virtual humans. In *Computer Graphics Forum*, volume 21, pages 327–335. Wiley Online Library, 2002.

[2] H. Harms, O. Amft, M. Appert, R. Müller, and G. Tröster. Wearable therapist: Sensing garments for supporting children improve posture. In *Proceedings of the 11th UbiComp*, pages 85–88. ACM press, 2009. Acceptance rate: 19%.

[3] H. Harms, O. Amft, D. Roggen, and G. Tröster. Influence of a loose-fitting sensing garment on posture recognition in rehabilitation. In *Proceedings of the Biomedical Circuits and Systems Conference*. IEEE press, 2008.

[4] D. House and D. Breen. *Cloth modeling and animation*. AK Peters, Ltd. Natick, MA, USA, 2000.

[5] J. Knight, D. Deen-Williams, T. Arvanitis, C. Baber, S. Sotiriou, S. Anastopoulou, and M. Gargalakos. Assessing the wearability of wearable computers. *Proceedings of the 10th ISWC*, pages 75–82, 2006.

[6] C. Mattmann. *Body posture detection using strain sensitive clothing*. PhD thesis, ETH Zürich, Nr. 17982, 2008.

[7] mysmithmicro. Poser 6. http://my.smithmicro.com/, 2012. [Online; last accessed 01-Jul.-2012].

[8] P. Volino and N. Magnenat-Thalmann. Accurate garment prototyping and simulation. *Computer-Aided Design & Applications*, 2(1-4), 2005.