Measuring Joint Movement Through Garment-Integrated Wearable Sensing

Guido Gioberto
University of Minnesota
Computer Science and Engineering
4-192 Keller Hall
200 Union Street SE
Minneapolis, MN 55455
gioberto@cs.umn.edu

Brief biographical Sketch

I am a Ph.D. candidate in Computer Science and Engineering at the University of Minnesota, in the United States. My research area is Wearable Sensing in Electronic-textile technology. I identify my research focus by using the following terms: "garment-integrated body sensing". I am interested in garment integrated sensors that monitor the human body, in particular the body movements. My research adviser is Dr. Lucy Dunne. She is an affiliate faculty member in Computer Science and an associate professor in Apparel and Design, at the University of Minnesota. Such collaboration helps me to understand the best way to introduce new solutions in the E-textile area also from a fashion design perspective, for example by looking at the perceptibility of the wearer, as well as at comfort variables.

UbiComp'13 Adjunct, Sept 8-12, 2013, Zurich, Switzerland.
ACM 978-1-4503-2215-7/13/09.
http://dx.doi.org/10.1145/2494091.2501085

Author Keywords

E-textile, wearable technology, smart clothing, wearable sensor, stitched sensor.

ACM Classification Keywords

H.1.2. User/Machine Systems: Human factors; I.2.9. Robotics: Sensors.

Abstract

Garment-Integrated body sensing is an alternative approach to sense body movements in wearable sensing. Textile-integrated sensors have the potential to equip everyday clothes with smart capabilities, making the detection of body movements accessible during normal life activities. The practicality of this solution preserves variables directly related to the wearer's needs such as Comfort, Perceptibility, and Awareness that must be prioritized equally with Accuracy and Precision of the sensor data. The central contribution of this approach is to improve the quality of the measured data while preserving user comfort.

Introduction

Body sensing through textile and garment structures has become an essential component to many pervasive systems, and has important applications from medical monitoring to human-device interface. As the field of wearable sensing develops, it has become clear that the second-skin approach that characterized many early prototypes (an approach that uses a skin-tight garment or suit to help the sensor to stay as close as possible to the surface of the body) presents problems of physical and emotional comfort, as well as logistics in dressing and use, that are prohibitive to the ultimate success of the wearable system in everyday use due to reluctance on the part of users or observer effects of the technology [3]. It is often the case that variables that promote comfort and ease of use for the wearer are often directly opposed to variables that improve the accuracy of the worn sensor. This tradeoff presents one of the most significant obstacles to widespread adoption of wearable sensor systems: sensing garments that are wearable and acceptable to the everyday user significantly limit the utility of the sensor, and sensing garments that produce high-quality data significantly limit the feasible user group and/or expected compliance level.

We find that measuring and analyzing the movement of garments of specific properties relative to the body surface is an essential component in overcoming the comfort/accuracy tradeoff of wearable sensing. Similarly, traditional sensing techniques often rely on components and approaches developed for sensing outside of the wearable environment, and consequently do not often prioritize the physical comfort of the component parts. This gap in available options has led to the development of textile-based sensing techniques which integrate the comfort properties of fibers, yarns, and textiles with electrical properties to yield sensing abilities. Here I discuss first my previous work in measuring and analyzing garment movement, and in developing comfortable, textile-integrated sensors. The remainder presents my plan for future work which synthesizes these two approaches in the development and validation of a wearable, comfortable garment capable of measuring and monitoring the movement of the knee.

Garment Movement Measurement and Error Analysis

Error introduced into a wearable sensor signal by garment-related parameters is evident in many application areas. Sensor movement affects most wearable sensors, but is particularly problematic for electro-dermal sensors [4] (that sense things like heart and muscle activity) and inertial sensing units [5] (accelerometers, magnetometers, and gyroscopes, which sense position and movement). The most common approach to managing movement noise in wearable sensors is prevention: through tight mechanical coupling by attaching the sensor to the body using elastic, straps, adhesive, or a skin-tight garment (e.g., [6]). In cases where improving mechanical coupling in surface sensors is not sufficient to reduce or remove motion artifact (such as in situations where the garment cannot apply sufficient force to the body, or where the wearer's movement is sufficiently vigorous), other countermeasures have been investigated, such as arrays of redundant sensors [7]. Harms et al. have undertaken significant study of the impact of garment movement on sensor signal quality, both in measuring the effects [8], and in modeling the impact of sensor orientation and textile folds using a simplified model of textile and garment properties [9]. Their work focuses primarily on the effects of movement and fabric wrinkles on inertial sensors. Our previous work established a method of measuring the movement and position of a garment relative to the body surface [10] (which is implemented here as well), and employed this method to explore the variability in error measured over the lower body [11].

Figure 1. Garment Movement Experimental Setup

To initially explore the potential effect of garment movement on sensor signals, we first conducted experiments to analyze the garment movements of a pair of pants during a walk/run. We used an IR motion capture system (BTS Smart-E, BTS Bioengineering, IT) which collects position samples of retro-reflective markers on a 3D coordinate space (X, Y, Z), with nominal frequency of 60Hz.

We tested 25 pairs of custom made Denim jeans: we used 5 fabrics different for weight and stiffness, and for each fabric 5 jeans sizes [1]. Our methodological approach can be summarized in the following three bullets:

- *Data collection method*. Jeans were worn by the animatronic running mannequin (Fig. 1). For each test, two separate experiments were conducted: markers were placed in strategic locations on top of the jeans and on top of a skin tight suit always worn by the running mannequin, in the exact same location. In this manner, a spatial reference for each marker, at each time instance, is defined. For each time instant the average Euclidean distance over all run gait cycles of each marker was computed providing an average estimate of the garment ease (see [1], *formula (1)*). Such average Euclidean error was then averaged again for all time instants, in order to extract a unique statistic for the markers distribution (see [1], *formula (2)*).

- *Error quantification*. The Euclidean error distribution with respect to the marker locations shows larger value around the hip area, while it is smaller around thigh and calf, respectively [10]. In [1] we characterize the markers distribution properties and describe the settling behavior of the Drift Error.

- *Movement error analysis*. Analysis of all markers for all fabrics and sizes yielded unwieldy and noisy results. To simplify this analysis, markers were grouped by vertical levels according to their body location, and Euclidean distances were averaged over different fabrics of the same size. We have found a repeated pattern, shown in the following Figure 2. Increasing the sizes, we notice that the Euclidean distance between same levels on skin tight suit and pants increases almost linearly, for all levels. An analysis by level for each of the fabrics allows finding consistent pattern between sizes, with the larger sizes that show greater ease.

These last results are still general and do not reflect the variability of the entire gait cycle. We believe the approach adopted may be a promising direction for future investigation looking more closely at the "remaining" noise after that positioning and drift error are taken out.

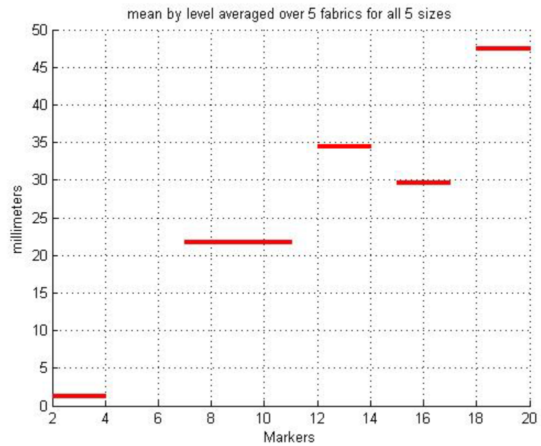

Figure 2. Average by level over all fabrics and sizes (markers 5 and 6 were corrupted)

Textile-Based Stretch Sensing

There are a number of methods currently in use or in development that measure stretch or elongation. [12][13][14]. The looped-conductor method uses a looped conductor of specific resistance per unit length, in which the loops of the conductor pass in and out of contact as the textile structure is stretched and relaxed (Fig. 3). In our paper [2], we implemented the loop structure using a conductive yarn and a very common type of apparel sewing machine, the coverstitch machine: when the stitch is relaxed (loops in contact) the electrical resistance decreases; conversely, when the stitch is stretched (loops separated) the electrical resistance increases.

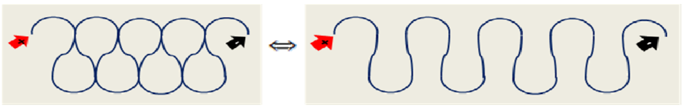

Figure 3. Looped Conductor Method of Stretch Sensing

The Stitched Sensor response is therefore originated by two stretching modalities: extension and recovery. Implementing the looped-conductor method in a stitched sensor as we described in [2], generates a resistance increase when the stitch is in extension mode and a resistance decrease when the stitch is in recovery mode. By changing the geometrical structure of the stitch makes it possible to realize a stitched sensor with an "inverse" working principle, where the resistance decreases during the extension mode and increases during the recovery mode.

We have also recently discovered that shorting properties of the stitch make the resistance decrease when the stitch is bent [16].

Textile-Based Bend Sensing

Bend Sensing has not been investigated in depth in our experiments yet. I believe it can potentially be used as an alternative to Stretch sensing or as a hybrid solution. We recently introduced a novel method based on garment stitched sensor for detecting bend [16]. Sensor responses to folding showed good correlation with knee bend angle and repeatability. Dunne et al. [15] developed and tested Garment-Integrated Plastic Optical Fiber (POF) sensors for monitoring seated spinal posture. Results showed that the sensor is capable to provide reliable and accurate measurements.

Stretching and Bending capabilities combined with the ease of integration with textiles and garments make both sensors well suited to monitor body movement, especially in measuring simple joint articulations such as Flexion or Extension. If multiple sensors are implemented in strategic ways, more complex articulations such as Rotation can be detected. The knee is a type of hinge joint that permits motion only in one plane where the movement is Flexion/Extension. In terms of utility, the knee supports the whole weight of the body, thus it tends to be more susceptible to injuries than other joints. Many Knee problems are connected to rehabilitation exercises aim to recover the flexion/extension movements of the knee.

Currently, I am testing the bend response of the stitched sensor in laboratory conditions to fully characterize the response to simple non-contact bends, complex (multiple folds) non-contact bends, and both simple and complex full-contact folds. Once this is complete, I will compare the results to our mannequin and human data in order to implement a knee-sensing garment as described below.

Future Direction

My thesis research will follow two major phases: First, I will assess the surface and joint-axis movement of the knee to determine the best-case sensor placements in several garment ease conditions (following the method previously developed, as described in the first section), validate the results of these motion-capture experiments using garment-integrated bend and stretch sensors, and quantify the accuracy of a best-case garment with integrated bend and stretch sensors; Second, I will integrate these results to develop and/or implement a joint-measurement algorithm.

I am currently testing our novel stretch and bend sensors [2, 16] integrated around the knee area on different sizes of stretchy pants, in order to find the best placement and location for them. I found that the stretch experienced by the pants area of maximum stretch after knee bend (identified on the very front of the knee) corresponds to a small elongation when the knee is fully bent because the stretch is absorbed from other regions of the garment that stretch and move at the same time. I am planning to overcome this problem by either adding design elements to the surrounding regions in order to constrain to zero the amount of stretch experienced during bend; or, by using both top and bottom conductive thread in combination for the same coverstich so as to have two isolated stretch sensors to monitor the exact same small amount of garment elongation, theoretically improving the accuracy of the stretch detection. Larger sizes should correspond to a smaller stretch to be detected, which will make the problem even more challenging. I expect to find the upper bound for the largest stretchy pants size (or pants fit) for reliable knee bend detection.

The outline of the remaining work for my dissertation can be summarized in:

- Further investigation of Bend Sensing modality.
- Additional characterization of both stretch and bend sensors in lab conditions and in garment-integrated testing on mannequin and human subjects
- Development and evaluation of a best-case knee-bend sensing garment.
- Development of joint measurement heuristics / algorithms for sensing garment.

The ***objective*** *of my thesis work is to develop a garment-integrated sensing method to characterize knee angle, to measure the accuracy of the garment-integrated sensing method, and to contextualize and validate this accuracy by comparison to the accuracy requirements of benchmark wearable sensing applications.*

The ***long-term goal*** *is to enable accurate wearable body sensing in loose-fitting (i.e. comfortable) clothes*.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation under grant number IIS 1116719. A very special thanks to the University of Minnesota, Dr. Lucy Dunne, and all Wearable Technology Lab collaborators.

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