Smart Garments: An On-Body Interface for Sensory Augmentation and Substitution

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Abstract
The human sensory network provides an immediate interface by which to gauge ambient properties of the environment, registering pressure, sound, odor, etc. However, sensory loss can drastically diminish one’s ability to process such ambient information, exposing an individual to potentially harmful situations. Smart Garments, capable of computation, communication, sensing, and actuation, have the ability to offset potentially hazardous circumstances associated with sensory loss by augmenting the human sensory capabilities. This research explores how Smart Garments can support those with a hearing impairment by leveraging the proximity and surface area of the human skin to provide contextual information (vibrotactile cues approximating the direction of critical environmental sounds) to a user.

Author Keywords
Haptic interface; wearable technology; distributed computation; hearing impairment; sensory substitution

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

Introduction
My research proposes developing Smart Garments with the ability to augment certain forms of sensory loss (e.g., hearing loss) by creating interactive materials that tightly integrate sensing, computation, communication, and actuation. These materials are dubbed “Computational Robotic Materials” (CRMs) and are networked together to perform localized, distributed computation. Smart Garments have the ability to supplement sensory loss and occlusion by using textile-embedded CRMs to interface between a human being and the environment. Skin stimulation can be seen as one of the predominant modes of
information conveyance due to a garment’s natural coupling with the skin. The density of nerve endings in fingertips make them ideal for fine-grain tactile input. However, developing a hands-free system derives a number of functional benefits as hands are often overloaded with having to perform daily tasks, such as carrying objects, typing, or opening doors.

This research proposes the development of a Smart Garment, in the form of a shirt, which uses tactile feedback to convey the direction of critical environmental auditory information to a deaf or hearing impaired user. The advantage of a Smart Garment is that it can unobtrusively remain on the user as one moves throughout the environment. Furthermore, a Smart Garment can leverage the skin’s large surface area to inconspicuously convey contextual information. Additional benefits include the fact that Smart Garments are hands-free, secure, and customizable (CRMs can be reprogrammed for the desired application) to the user and the specific degree of disability. We see such Smart Garment technology as extending past the assistive domain into multiple industry applications including gaming, navigation, military and medical fields, communication, and health and fitness.

**Related Work**

Previously explored textile-based forms of wearable technology include the wearable Motherboard developed at The Georgia Institute of Technology [1], Gorlick’s Electric Suspenders [2], and e-Tags by Lehn et al. [3]. However, these garments were limited in application scope and processing power due to the restrictive nature of centralized processing units [1] and the dedicated bus systems employed [2], [3], thus reducing the number of devices they could support and also making the system susceptible to failure due to single points of bus failure or node malfunctions. Given the advancements in distributed networking power and the downsizing of the physical form factor of microcontrollers, CRM technology can enable wearable computing applications that were not previously viable. A scalable system could not have been implemented to the same degree using a centralized, computing infrastructure. My work explores how a tight coupling of local sensing and actuation using the CRM distributed computation network can be used to create robust wearable interface systems extensible to a number of users and applications.

**Smart Garment Prototype**

The original Flutter prototype (see Figure 1) was created to augment hearing loss by giving vibrotactile cues to indicate the direction of critical information of the local sound topology (e.g., alarms/alerts). Instrumenting a garment to supplement sensory loss is made possible through the use of small microcontrollers capable of performing distributed computation. CRMs use a network of microphones to capture the local sound environment and then relay the directionality of warning signals (frequencies above a certain threshold and amplitude, such as police sirens) through co-located coin vibration motors. Tactile feedback gives an intuitive prompt to direct a user’s attention in a particular direction, similar to someone tapping you on the shoulder. Flutter was designed in the form of a dress to exploit a larger on-body surface area (i.e., feedback spanned from the lower shoulder blades all the way to the anterior mid-torso to convey both the direction and the elevation of sound, akin to how owl ears localize frequencies). The revised prototype (See...
Figure 2) will be tested only on the upper torso using CRMs to detect 6 circumferential sound directions.

**Methodological Approach**
System validation and application viability will be made possible through extensive user studies on the integrated Smart Garment system. Testing will occur in the Speech, Language, and Hearing Sciences Department at the University of Colorado – Boulder. Able-bodied, hearing-impaired, and deaf participants above the age of 18 will be recruited to participate in the study. Approximately 10 participants of each subject pool will be recruited. Prior to beginning the study, participants will be asked to complete a demographic and preliminary interview questionnaire on-site. Testing will take place in an audio booth with 6 equidistant speakers (direct front and back, with 60 degree spacing in between speaker placement) producing auditory tones simulating alerts found in the environment (e.g., a car horn). The directional order of the auditory stimuli will be counterbalanced. Participants will don the Smart Garment and undergo a brief tutorial of the system and will use a tablet with icons mapping to the sound direction to record their responses. Participants with full or partial hearing will undergo Treatments 1, 2, and 3. Deaf participants will participate in Treatment 1 (for consistency):

*Treatments*
1) Smart Garment/With Headphones (simulating deafness)
2) Smart Garment/Without Headphones
3) No Smart Garment/Without Headphones

Treatments 2 and 3 will be used to assess the participant’s innate auditory directional resolution.

Treatment 2 will help assess if those with a partial hearing impairment can use the co-located vest to more accurately resolve sound direction. While prior research has established human auditory localization to be much more precise than the 6 general directions proposed for our testing purposes, this study is to assess our hardware architecture as a viable option for sensory substitution, not to evaluate the precision of the human auditory system. For this reason, after consulting with Dr. Kathryn Arehart, an expert in audiology research in the Speech, Language, and Hearing Sciences Department at the University of Colorado - Boulder, we determined that 6 directions were sufficient for this study. The treatments will be counterbalanced to account for fatigue and learning. Upon completion of the study, a follow-up questionnaire will be administered to assess user experience.

**Research Phases**

*Existing Work*
A preliminary assessment of Smart Garment operation and accurate detection and conveyance of auditory information has already been conducted and IRB approval has been obtained. I have open channels to my sample population and recruitment is underway. At this stage, I am in a solid position to move forward with the testing of the Smart Garment system on human subjects. I first plan on conducting a pilot study using 3-5 participants to make sure that the testing facility and procedures are robust and comprehensible to participants.

*Remaining Work*
Recruitment and testing still remains to be completed. In addition to the devised study, I would like to revise the system based on the data collected and do follow-
up testing. Three avenues that I would like to pursue include: I) Physical Design of the system, II) User Interface Development, and III) Smart Garment Output and Information Conveyance. It is this portion of the remaining work that I think could greatly benefit from discussions at the Ubicomp Doctoral School.

I. PHYSICAL DESIGN
I would like to focus heavily on the design of the wearable for future Smart Garment iterations. A common concern related to assistive technology (AT) adoption focuses on the aesthetics and social acceptability of the device. A conspicuous device (such as a hearing aid) may often impede AT adoption as it calls attention to one’s disability. Given the fact that CRMs’ small form factor enables inconspicuous integration with a wearable, I am eager to explore the types of wearable devices (garment versus accessory) that participants would prefer. The follow-up questionnaires will be used to determine the most preferred types of wearable form factors and aesthetic properties, whether the system should be fully integrated into a garment or retrofitted, as well as the user experience features for the preferred types of system interaction and operation. Capturing user feedback can yield insight into the level of customization preferred by users.

II. USER INTERFACE DEVELOPMENT
Of interest would be a critical examination of the user interface, including surveys evaluating the maximum number of features, device setup (from both the user and caretaker perspective), and long-term use. Developing an intuitive user interface would permit for easy system reconfiguration for dynamic contexts (changing the device settings to respond solely to a car horn or a fire alarm) and ease of operation.

III. OUTPUT AND INFORMATION CONVEYANCE
A necessary component of a tactile feedback system is making sure that the tactile stimulus conveys the appropriate degree and type of information. Thus, I am interested in exploring differing spatio-temporal resolutions, tactile intensities, vibrotactile pulse sequences, and stimulation durations to assess the inherent mapping between environmental alert type and the information conveyed through the vibrotactile indicator. Previous work on intuitive vibrotactile mapping has been used for snowboarding instruction purposes in wearable training systems [7], [8]. These previous studies can be used as a foundation for generating our own mapping patterns to provide effective and consistent notification systems that are generalizable across user bases for applications that extend beyond supplemental hearing systems.

Objective for Attending the Doctoral School
I would like to attend the Doctoral School to garner input from researchers in the field regarding the direction of my dissertation work. My area of focus combines many distinct fields, namely, computer science, industrial and fashion design, human-computer interaction, assistive technology, and electrical engineering. This multi-disciplinary approach yields a large number of considerations which may or may not overlap. Sharing my work would allow me to convey how I envision this work coming together into a holistic, serviceable unit. I also hope to gain insight regarding new opportunities, unrealized directions and resources,
and additional design and study considerations for my work. While my study focuses on the deaf and hearing impaired constituencies, I believe that much of my research can be leveraged for more generalizable smart material development and on-body interface design. While I am still in the preliminary stages of my study, I believe that my work can be greatly informed through interactions with the DS panel and student participants to ensure that my research has a more meaningful contribution to the wearable computing and assistive technology domains.

**Biographical Sketch**

*Halley P Profita* is pursuing her Ph.D. in Computer Science at the University of Colorado – Boulder. She is housed in the Correll Robotics Lab and began her program in the fall of 2011 (anticipated graduated date is May 2016) with a concentration in Human-Centered Computing. Her graduate work predominantly focuses on Human-Computer Interaction and wearable computing design for assistive purposes. Her current advisory committee includes Dr. Nikolaus Correll (CU-Boulder), Dr. Clayton Lewis (CU – Boulder), and Dr. Michael Lightner (CU – Boulder).

*Dr. Nikolaus Correll* has been an assistant professor in the Dept. of Computer Science since August 2009 with courtesy appointments at the Dept. of Electrical, Computer, and Energy Engineering and the Dept. of Aerospace Engineering at the University of Colorado at Boulder. He obtained a Ph.D. from Ecole Polytechnique Federale De Lausanne (EPFL) advised by Dr. Alcherio Martinoli in 2007 and spent two years at MIT CSAIL working with Dr. Daniela Rus as a post-doc. Before moving to EPFL, Dr. Correll was a research assistant in the Collective Robotics Group at Caltech in 2003, also with Dr. Martinoli. Dr. Correll earned a Master’s degree in Electrical Engineering from the Swiss Federal Institute of Technology Zurich (ETH Zürich) in spring 2003. He wrote his master’s thesis in the Collective Robotics Group at Caltech, Pasadena, CA, USA, about collaborative coverage supervised by Dr. Martinoli and Dr. Joel Burdick, and spent a term at Lunds Tekniska Högskola as an exchange student at the Dept. of Automatic Control working with Dr. Rolf Johansson in 2002.

**References**


