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Intelligent Textiles for Physical Human-Environment Interactions

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ABSTRACT

Physical human-environment interaction is a fundamental aspect of our daily lives, involving the constant use of our sensory and motor systems to extract, process, and communicate information. Capturing, modeling, and augmenting these physical interactions are crucial for enhancing human well-being and promoting intelligent system designs. However, the pervasive and diverse nature of these interactions poses challenges that require scalable and adaptable systems. To address these challenges, I adopt an integrated approach that combines digital fabrication and machine learning techniques. The approach involves developing a digital design and fabrication pipeline to integrate sensing and actuation capabilities into textile-based platforms, and capturing diverse datasets on human-environment interactions to enable intelligent and adaptive applications. The dissertation showcases past and ongoing works on intelligent textile-based sensing and actuating platforms that embody this approach, including tactile sensing garments, an intelligent carpet for human pose estimation, programmable textile-based actuators for assistive wearables, and smart gloves for adaptive tactile interaction transfer. Moving forward, I aim to explore applications of the developed systems in healthcare, robotics, and human behaviors intervention, and expand to diverse sensing and actuation modalities.

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1 INTRODUCTION

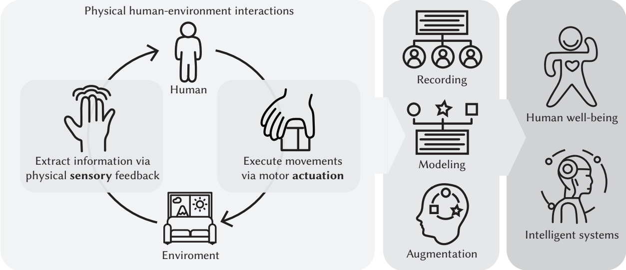

Figure 1: Research goal: recording, modeling, and augmenting physical human-environment interactions to enhance human well-being and promote anthropomorphic intelligent system designs.

Humans engage in a wide range of daily activities, spanning from basic motor skills such as walking and grasping objects, to complex tasks such as communication and learning, by constantly interacting with the external environment physically. Such physical human-environment interactions include extracting information through diverse sensory systems and executing motor movements through body parts and muscles. For example, when running, an individual extracts the force distribution between the feet and the floor through the tactile sensory feedback, while simultaneously adjusting body balance and pacing for subsequent steps through the actuation of corresponding muscles. Recording, modeling, and augmenting physical human-environment interactions are instrumental in driving progress across various fields such as healthcare, human-computer interactions, and robotics. These endeavors are crucial not only for enhancing human well-being through monitoring, understanding, and facilitating human behaviors, but also for advancing the development of intelligent systems, such as enabling intelligent robot manipulation through imitation learning and fostering the creation of interactive human-centric designs.

However, challenges arise from the **pervasive** and **diverse** nature of physical huamn-environment interactions. Physical human-environment interactions are pervasive both spatially and temporally, occurring throughout the body, across different environments, and over extended periods. Additionally, these interactions exhibit diverse characteristics during various scenarios, such as grasping, locomotion, and more. These interactions are also subjectively perceived and performed by individuals, involving different input-output modalities, including force and strain sensing, kinesthetic and muscular actuation, and so on. Addressing these challenges requires scalable, customizable sensing and actuating systems that seamlessly integrate into diverse individuals and environments.

Throughout my Ph.D., I have been exploring intelligent textiles as a means to capture, model, and augment human-environment interactions [3–8]. I tackle the challenges by adopting an integrated approach that leverages advances in both digital fabrication and machine learning. My approach consists of three key aspects: 1) **developing a digital design and fabrication pipeline** to seamlessly integrate sensing and actuation capabilities into flexible and conformal textile-based platforms in a scalable and customizable manner; 2) **capturing diverse large datasets** on physical human-environment interactions; and 3) **leveraging advanced machine learning techniques** to enable intelligent and adaptive capabilities and applications.

In this dissertation, I showcase four intelligent textile-based platforms integrated **sensing** and/or **actuation** capabilities embodying our approach. The integration of sensing capabilities into

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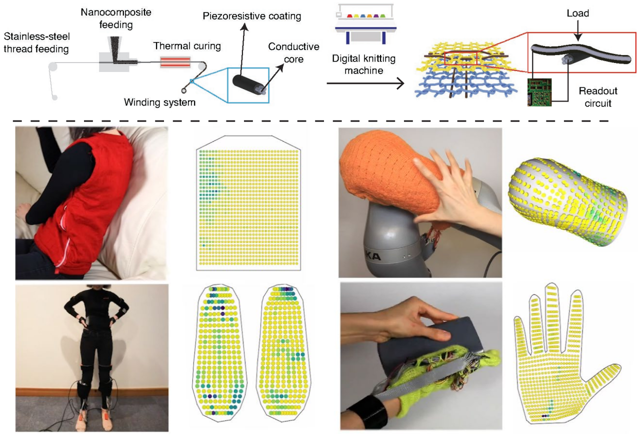

Figure 2: Top, The full-sized tactile sensing vest, robot arm sleeve, socks, and gloves were fabricated by integrating customized piezoresistve fibers through digital machine knitting. Bottom, The sensing garments were able to capture real-time diverse human-environment interactions.

scalable textiles enables the capturing of rich data on physical human-environment interactions. By applying advanced computational techniques, we are able to uncover patterns, correlations, and trends from the captured dataset. Furthermore, building upon the insights obtained from the modeling and analysis, we leveraged textiles with integrated actuation capabilities to output feedback for the augmentation of physical human-environment interactions. I will discuss the details of each of these platforms in the following sections.

2 SENSING

I start by introducing our work on developing scalable textile-based sensing platforms that enable the capture of physical human-environment interactions. Leveraging advanced machine learning techniques, we aim to model and comprehend human behaviors based on the large dataset collected through these platforms.

2.1 Tactile Sensing Garments

Despite recent innovations in advanced materials, designs, and manufacturing techniques, sensory interfaces that offer conformal, full-body coverage for the capturing and analysis of whole-body tactile interactions remain challenging. We for the first time present **full-sized tactile sensing garments for capturing and learning on human activities** [5]. These conformal soft tactile sensing garments, including vest, socks, gloves, and coverings for arbitrary 3D shapes, were digitally designed and automatically fabricated via a digital knitting machine.

To enable tactile sensing capabilities, we employed customized coaxial piezoresistive fibers, which were created by coating stainless steel threads with piezoresistive nanocomposites through a scalable automated process. By overlapping pairs of these fibers orthogonally, we created sensing units that convert pressure stimuli, i.e. normal forces acting on the surface, into electrical signals, with the highest achieved sensitivity of 1.75 kPa and a detection range up to 87.5 kPa. Through digital machine knitting, these piezoresistive fibers were transformed into sensing textiles that obtains arbitrary 2D shapes and conform to various 3D geometries.

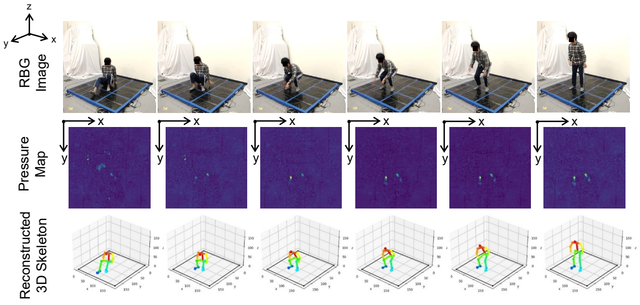

Figure 3: Our intelligent carpet captured tactile interactions of a person standing up from a sitting position, which was input to a trained neural network for 3D pose estimation.

Our sensing garments obtain up to 1024 pressure sensors, enabling real-time, seamless, and continuous capture of physical interactions between the human body (e.g., hands, feet, torso) and the external environment (e.g., objects, floor, furniture) (Figure 2). Leveraging the captured large and diverse datasets, we developed machine-learning models to calibrate the extensive sensing arrays and extract meaningful features from these interactions, with the aim of modeling and understanding human behaviors. For examples, we demonstrate the capabilities of our system in object classification, action classification, pose estimation, and gait signature discovery.

The system has been further extended to customized sensing robots and manipulator skins [9, 11], dynamic modeling of human-object interactions [10], and multimodal data capturing of complex human manipulation tasks for robot learning [2]. Overall, our full-sized tactile sensing garments represent a significant advancement in capturing and learning from human activities. The integration of conformal sensing textiles across the body opens up possibilities for various applications, ranging from understanding human behavior to enhancing human-robot interactions.

2.2 Intelligent Carpet

Humans exert force on the floor during exercises and daily activities, providing valuable insights into their motions and health conditions. To capture and analyze these physical human-floor interactions, we have developed **an intelligent carpet to capture human-ground tactile interactions for 3D pose estimation** [4]. The intelligent carpet is composed of a piezoresistive pressure sensing matrix fabricated by aligning a network of orthogonal conductive threads as electrodes on each side of the commercial piezoresistive films. Each sensor locates at the overlap of orthogonal electrodes and is able to measure pressure up to 14 kPa with the highest sensitivity of 0.3 kPa. Our tactile sensing carpet is low-cost (around 100$), obtains over 9000 pressure sensors, covers more than 36 square feet and can be seamlessly embedded to the floor. With accompanying readout circuits, our system enables real-time recording of high-resolution pressure imprints during various human daily activities.

Using this hardware, we collected a vast dataset of over 1,800,000 synchronized tactile and visual frames involving 10 individuals performing diverse daily activities, such as lying, walking, and

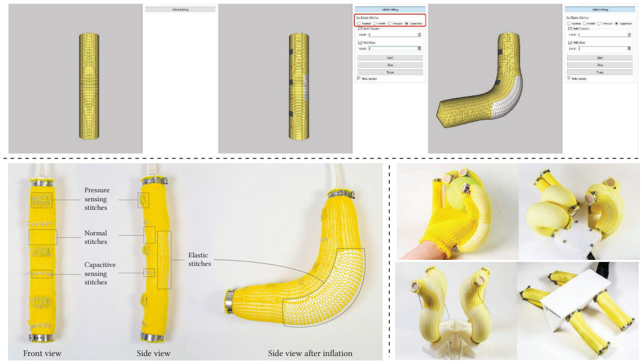

Figure 4: Top, Our interactive design interface for machine-knitted pneumatic actuators with simulated deformation. Bottom left, A typical actuator is programmed by strategically placing conductive, elastic, and normal stitches throughout the knitted sheath. Bottom right, Application scenarios of our machine-knitted pneumatic actuators.

exercising. Leveraging the visual information as supervision, we designed and implemented a deep neural network that uses only tactile information to infer the corresponding 3D human pose. Remarkably, our network achieves an average localization error of less than 10 cm compared to the ground truth pose obtained from visual information. Moreover, our approach can be scaled up for multi-person 3D pose estimation. Furthermore, by combining the learned representations from the pose estimation model with a simple linear classifier, we achieved an impressive action classification accuracy of 98.7%.

The intelligent carpet system we have developed not only enables human pose estimation that remains unaffected by visual obstructions but also opens up possibilities for various downstream tasks, including gaming, gait analysis, and behavior monitoring [1]. The seamless integration of tactile sensing into the floor provides a confidential and unobtrusive means of monitoring human activities and extracting valuable insights for a range of applications.

3 ACTUATION

I will then introduce our development of scalable textile-based actuating platforms that enable the augmentation of physical human-environment interactions. Building upon the valuable insights on physical human-environment interactions, we aim to facilitate and enhance human behaviors by providing feedback via personalized, adaptive, and seamlessly integrated actuation capabilities in textiles.

3.1 Programmable Pneumatic Actuators

To further enhance physical human-environment interactions, we have successfully integrated pneumatic actuators into conformal textiles using digital machine knitting. Traditional approaches for textile-based pneumatic actuators involved labor-intensive fabrication processes and limited interaction possibilities. In contrast, **our method enables scalable, seamless, customizable, and modeled integration of pneumatic actuators in textiles** [7].

Specifically, our actuator is composed of two parts: an off-the-shelf thin-wall silicone tube, which serves as the base pneumatic channel, and the knitted sheath with programmed stitches, which wraps over the silicone tube and confines the shape of the inflated actuator. Leveraging the variation in Young's modulus enabled by elastic yarn and acrylic yarn, we programmed the local extensibility and stiffness of the machine-knitted sheath by strategically placing elastic stitches between normal stitches throughout the knitting procedures. By doing so, we controlled the actuation response and forced the tube to bend, transforming an isotropic and symmetric behavior into one that is directed and can perform useful work. Our actuators can bend with curvatures up to 0.2 m^{-1} and exert forces up to 9 N at the tip. Moreover, we integrate pressure sensing and swept frequency capacitive sensing capability with the actuators via a carefully constructed secondary conductive layer leveraging various machine knitting techniques (Figure 4 bottom left).

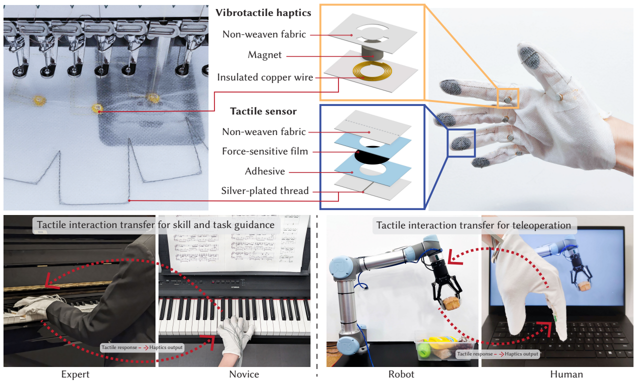

Figure 5: Top, A digitally embroidered smart glove with tactile sensing array and vibrotactile haptic array. Bottom, We aim to perform adaptive tactile interaction transfer to promote human skill development and teleoperation.

The digital machine knitting process offers programmable and rapid fabrication. Leveraging physically-based simulation techniques, we offer an interactive user interface (Figure 4 top), allowing users to design and preview actuators' shapes under pressure quickly. After users have finalized their design, the whole knitted structure, including elastic and sensing stitches, is fabricated automatically in one machine run. We demonstrate our system's utility by using it to build assistive wearables, interactive devices, robotic grippers, and locomotive soft robots (Figure 4 bottom right). Our approach offers a programmable textile-based actuating platform for huge potential in seamlessly integrated and personalized assistive wearables to augment physical human-environment interactions.

3.2 Smart Gloves for Adaptive Tactile Interaction Transfer (On-going)

Taking a step further, we aim to utilize the collected and modeled data on physical human-environment interactions to enable intelligent and adaptable augmentations to humans' behaviors and experiences during daily activities. As a proof of concept, we demonstrate **tactile interactions transfer via smart gloves with integrated tactile sensing and vibrotactile haptic array**.

Enabling seamless and intuitive transfer of tactile interactions is crucial across various domains. However, it remains a significant challenge due to the need for scalable and flexible tactile sensing and haptic display systems that seamlessly integrate into our daily lives. While prior studies have showcased the immense potential of such systems, they have also highlighted obstacles such as complex and fragile fabrication processes, which limit scalability, durability, customization, and compatibility. Additionally, the variability in human perception of haptic feedback makes effective and reliable human-machine communication challenging, as personalized calibration should be minimized to ensure a seamless user experience.

We aim to move towards addressing many of these challenges in sensing, feedback, multimodal integration, and adaptive control by presenting a textile-based wearable human-machine interface as well as its fabrication approach and control algorithms. We integrate tactile sensing and vibrotactile haptic feedback using a customizable and scalable computational fabrication pipeline, develop designs that can be applied to various domains, and create a machine-learning pipeline for per-user haptic optimization.

Specifically, focusing on tactile interactions of the hands, we introduce a diverse set of smart gloves with integrated tactile sensors and vibrotactile units. Our digital design pipeline allows customization of the resolution and locations of tactile sensors and vibrotactile units. The integration of sensing and haptics is achieved automatically on the textile using conductive threads and enameled copper wires through digital embroidery. With coupled readout and driving circuits, the tactile sensors and vibrotactile haptic units serialize data and output feedback simultaneously. To assess the usability and effectiveness of our interface, we conducted a user study where 10 subjects evaluate and identify haptic feedback with different amplitudes, frequencies, temporal patterns, and locations on the hand. Furthermore, we developed a learning and optimization pipeline that compensates for variations in users' perceptions by learning a model of the human's response to haptic feedback, eliminating the need for manual calibration.

In the near future, we plan to leverage this textile-based wearable human-machine interface and its underlying algorithms to augment physical human-environment interactions through tactile information transfer. First, we aim to alleviate tactile occlusion by transferring forces sensed on the outside of the glove to haptic sensations applied on the person's hand inside the glove. Next, we will explore a skill-developing scenario that leverages the learning and optimization pipeline to adaptively transfer tactile interactions from experts to novices and improve task performance. The effectiveness of our method was demonstrated under three scenarios, including, piano playing, car racing gaming, and rhythmic gaming. Finally, we will investigate how transferring force sensations from a robot to a person can enrich teleoperation and enable more delicate grasping operations. We believe our initial attempt on tactile interactions transfer via digitally embroidered smart gloves with integrated tactile sensors and vibrotactile haptics steps towards enabling physical tactile interactions to persist across space and time and to be accessible simultaneously to multiple users and intelligent agents. It will open up exciting possibilities for enhancing human-machine interfaces and augmenting physical interactions between human and the environment.

4 CONCLUSION AND FUTURE WORK

This dissertation presents my extensive research on intelligent textile-based systems for capturing, modeling, and augmenting physical human-environment interactions. Leveraging digital design and fabrication pipelines, I successfully constructed scalable, customizable, and seamless wearables embedded with integrated functionalities, such as tactile sensors, pneumatic actuators, and vibrotactile haptics. These advancements have enabled the comprehensive capturing and augmentation of pervasive and prolonged physical interactions between humans and their external environment. Additionally, I leveraged the power of machine learning to establish an intelligent and adaptive computation pipeline, effectively modeling and enhancing diverse and subjective physical human-environment interactions.

Looking ahead, future work will build upon the solid foundations established in this dissertation, further exploring their new applications in healthcare, human-computer interactions, and robotics. One intriguing application is the potential of the developed tactile sensing garments and large-scale environmental tactile sensing coverings to serve as a natural and unobtrusive means of gathering data for diagnosing and monitoring diseases like Parkinson's. Furthermore, our advancements in robust and scalable tactile sensors hold promise for applications in robotics. For example, the captured data on physical human-environment interactions can provide valuable inside for robot imitation learning, allowing intelligent agents to learn from physical human demonstrations and effectively perform tasks requiring dexterous manipulation and natural interactions with the environment. Applying such sensors on robots will empower intelligent systems with the ability to perceive tactile sensations akin to those of humans, which enables robots to execute tasks and engage in interactions in a manner that closely resembles human behavior.

In addition, future research can focus on the modeling and intervention of human behaviors via smart textiles equipped with integrated sensing and actuation capabilities. This can be achieved by continuously sensing and modeling human behaviors, and subsequently intervening in these behaviors through real-time actuation feedback. Such closed-loop interface presents exciting opportunities for further understanding, exploration, and refinement on human behaviors for diverse domains. The theme of capturing, modeling, and augmenting physical human-environment interactions can also be extended to a multimodal setting. This entails combining and interchanging diverse sensing modalities, such as strain sensing and vibration sensing, as well as employing various actuation modalities, including electrical stimulus and magnetic actuation. The incorporation of multimodal capabilities will address more complex scenarios and tasks, significantly enhancing our overall understanding and expanding the range of applications in diverse fields.

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