Weaving Physical and Physiological Sensing with Computational Fabrics

Qijia Shao
qijia@cs.columbia.edu
Columbia University
New York City, NY, USA

ABSTRACT

Accurate, continuous monitoring of human physical and physiological signals is critical to enhancing healthcare, personalizing education, and human interaction with the physical environment. Current methods for acquiring human data, however, frequently rely on cumbersome environmental instrumentation, extensive manual inputs, or uncomfortable rigid or adhesive wearable sensors. The emergence of computational fabrics has ushered in a new era of ubiquitous computing. By seamlessly integrating sensing capabilities into everyday clothing and accessories, we enable uninterrupted physical and physiological data acquisition and interpretation, providing a holistic view of an individual's status.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing systems and tools**.

KEYWORDS

Computational Fabrics, Physical Sensing, Physiological Sensing

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1 INTRODUCTION

Human states are fundamentally influenced by physiological signals and manifested through physical signals. Accurate, continuous monitoring of human physical and physiological signals is critical to different applications (e.g., enhancing healthcare [3, 4], personalizing education [5], and facilitating human interaction with ambient environments [2]). However, current data acquisition methods continue to encounter specific challenges inherent to each methodology. The first challenge involves extensive environmental instrumentation, which, although effective, is resource-intensive and confined to specific settings like hospitals or movie studios, limiting its scope for widespread, continuous monitoring. The second issue relates to the substantial manual effort required for data acquisition, which is time-consuming and prone to human error, resulting in inconsistent data. Thirdly, while wearable sensors facilitate continuous monitoring, their rigidity or adhesive properties can lead to discomfort and skin irritation, particularly for sensitive groups such as the elderly or infants. In this context, current human data acquisition methods are increasingly inadequate.

We introduce computational-fabrics-based system design and robust data analytics to overcome these barriers in acquiring and interpreting physical and physiological signals. Fabrics, inherent to our daily attire, present a ubiquitously available, cost-effective medium for mass production, offering unparalleled comfort for wearers. Being already incorporated into daily wear, fabrics enjoy higher social acceptance compared to devices like smartwatches, which are still perceived as optional accessories. These position them as an ideal candidate for unobtrusive continuous monitoring. While previous research in e-textiles has explored various applications, it has generally been limited to basic physical sensing capabilities. Our work on *Computational Fabrics* aims to enhance the state-of-the-art in both sensing capability and reliability while maintaining the inherent unobtrusiveness and comfort of fabrics. Notably, we focus on affordable, off-the-shelf conductive fabrics for comprehensive sensing without additional electrical sensors.

Challenges. Implementing the concept of computational fabrics as viable, deployable systems presents several practical challenges. *First*, the fabrics' intrinsic flexibility complicates achieving consistent contact with the human body—a critical factor for accurate data collection. Insufficient contact may introduce motion artifacts. *Second*, the data variability due to individual differences, poses significant challenges in ensuring system generalizability across new user populations. This challenge is compounded by the ever-changing ambient environment, which introduces various interferences. Developing algorithms capable of handling diverse noise types is thus essential. *Third*, the use of tiny computing units to maintain system unobtrusiveness imposes limitations on computing power and battery life. Developing analytic models that can operate efficiently on such constrained platforms is a non-trivial pursuit, demanding innovative approaches to ensure their practicality and effectiveness.

Contributions. In addressing the challenges presented, our approach is problem-driven, leveraging insights from material science and expertise from domain experts. Our methodology integrates system design with scalable and efficient data analytics, creating custom solutions tailored to the diverse requirements of specific use cases. For scenarios with substantial data, we employ neural network-based algorithms enhanced by adversarial training [1]. This technique identifies features with minimal dependency on user and environmental variables, optimizing model robustness and applicability. In situations where large datasets are scarce (e.g., medical

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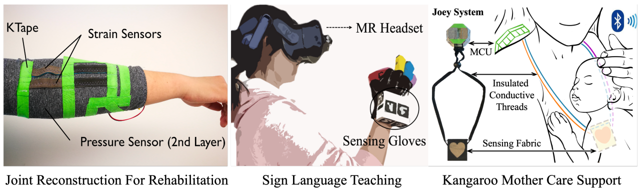

Figure 1: Computational-fabrics-based sensing systems.

applications), we construct mathematical models employing normalization strategies to achieve generalization across varied conditions [6]. Furthermore, our approach includes a software-hardware co-design, strategically minimizing computational overhead and power consumption [4]. This optimization is crucial for deploying effective, energy-efficient computational fabric systems capable of real-time analysis and long-term operation. Through these strategies, we address the inherent challenges of computational fabric technology and pave the way for innovative applications in wearable computing and beyond.

Next, we showcase some of our explorations into fabric-based systems (see Figure 1) and discuss potential future directions.

2 PHYSICAL SENSING

Accurate and continuous monitoring of joint rotational motion is crucial for a wide range of applications such as physical rehabilitation [3], and motion training/coaching [5].

Our work [3] utilizes off-the-shelf stretchable conductive fabrics. The sensing ability of such fabrics stems from their knitted microstructures of the yarns. External strain caused by joint movement alters the fabric's resistance, enabling the inference of joint angles. We address fabric sensing challenges, originating from the properties of elastic materials, by leveraging stretchable and pressure fabrics, and characterizing their properties through material science models. Applying biomechanical models to infer joint angles, we suggest dual strain sensing to improve sensing robustness against user diversity and fabric position offsets. We fabricate prototypes using off-the-shelf fabrics. Experiments with ten participants show a 9.69-degree median angular error in tracking joint angle and its sensing robustness across various users and activities.

Then we extend the same sensing mechanism to a custom glove, designed to capture finger joint motion without occlusion issues [5]. With the custom glove as the input device, we developed a holistic teaching system with real-time feedback in mixed reality to allow the user to perceive her own hands in an immersive learning environment with first- and third-person views for motion demonstration and practice, significantly enhancing American Sign Language (ASL) learning.

3 PHYSIOLOGICAL SENSING

Physiological sensing is essential for monitoring the internal functions of human body. Traditionally, physiological sensing has relied on specialized equipment, which often necessitates visits to medical facilities and disrupt daily activities, making it impractical for continuous use. Our research advances physiological sensing with computational fabrics, introducing unobtrusive systems that support comfortable, continuous monitoring for a range of applications.

ECG. One of the applications we work on is Kangaroo Mother Care (KMC), which involves skin-to-skin contact between an infant and a caregiver [4]. Monitoring the duration of KMC and the infant's vital signs is crucial, yet current methods rely on manual recording and the use of rigid sensors/wires attached to the infant, which are cumbersome. To address these challenges, we introduce "Joey," a soft fabric necklace worn by the caregiver that utilizes the transmission of ECGs during skin-to-skin contact. Joey detects the mixed ECGs to measure KMC duration and then separates the infant's ECGs from the mixture using a novel signal extraction algorithm and applies a diffusion-based denoising model to reduce motion artifacts. This approach enables accurate determination of the infant's vital signs.

EMG. The successful implementation of Joey underscores the potential of computational fabrics in biopotential monitoring, paving the way for our current project on sleep posture monitoring through neck electromyography (EMG) signals. Sleep posture has been linked to disease progression and overall health, making its monitoring critical for improved patient care and for individuals to minimize health risks by adjusting sleeping positions. Traditional sleep posture monitoring methods fall short in comfort.

We are developing an EMG-based smart pillow with computational fabrics, which offers non-invasive, continuous sleep posture monitoring. This approach leverages the universal use of pillows—utilized by over 95% of people—eliminating the need for additional, intrusive equipment. The current design ensures the pillow retains the comfort and feel of a normal pillow, thus preserving natural sleep patterns. The smart pillow uses a conductive fabric sensor array to detect variations in neck muscle tension associated with different sleep postures. However, the variability in sleeping postures leads to different muscle groups coming into contact with the sensor, thereby altering the EMG signals corresponding to various muscles. Additionally, there is the challenge of inter-individual differences in muscle response. To address these challenges, we are actively working on enhancing the adaptability and accuracy of our smart pillow system. We aim to refine the signal processing and machine learning algorithms to better accommodate the wide range of individual differences and sleep patterns, ensuring that our solution is both highly effective and universally applicable.

4 THE ROAD AHEAD

Human neurons are constantly engaged in transmitting commands through bio-potentials to control how we interact with the physical world. Physical sensing captures these end behaviors, offering a snapshot of human interaction with our environment. At the same time, by observing the physiological signals such as ECG, EMG, and electroencephalogram/EEG that underpin physical actions, we could obtain deeper insights into the motivations and mechanisms driving these behaviors. This holistic approach, merging physiological observation with physical sensing, brings a new frontier in understanding human behaviors. Such an integrated sensing paradigm not only enriches our grasp of human biomechanics but also opens vast possibilities for advancements in targeted healthcare, personalized education, and adaptive entertainment experience. Navigating this path involves challenges like the weak signal-to-noise ratio in EEG and EMG signals, significant motion noise, and complex signal dynamics. Addressing these issues demands innovation and continuous research to improve integrated sensing technologies. Our goal is a future where comprehensive sensing is as intuitive and seamless as the neural commands that guide us.

5 SHORT BIOGRAPHY

Qijia Shao is currently a Ph.D. candidate in Computer Science at Columbia University, under the supervision of Professor Xia Zhou and Professor Fred Jiang. His research interest lies broadly in the application-driven aspects of Mobile Computing and Human-Computer Interaction, with a recent focus on the development of unobtrusive physical and physiological sensing systems.

REFERENCES

[1] Vimal Kakaraparthi, Qijia Shao, Charles J. Carver, Tien Pham, Nam Bui, Phuc Nguyen, Xia Zhou, and Tam Vu. 2021. FaceSense: Sensing Face Touch with an Ear-worn System. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 5, 3, Article 110 (sep 2021), 27 pages. https://doi.org/10.1145/3478129

[2] Pin-Sung Ku, Qijia Shao, Te-Yen Wu, Jun Gong, Ziyan Zhu, Xia Zhou, and Xing-Dong Yang. 2020. ThreadSense: Locating Touch on an Extremely Thin Interactive Thread. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376779

[3] Ruibo Liu, Qijia Shao, Siqi Wang, Christina Ru, Devin Balkcom, and Xia Zhou. 2019. Reconstructing Human Joint Motion with Computational Fabrics. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 3, 1, Article 19 (mar 2019), 26 pages. https://doi.org/10.1145/3314406

[4] Qijia Shao, Jiting Liu, Emily Bejerano, Ho Man Colman, Jingping Nie, Xiaofan Jiang, and Xia Zhou. 2024. Joey: Supporting Kangaroo Mother Care with Computational Fabrics. In *Proceedings of the 22nd Annual International Conference on Mobile Systems, Applications and Services* (Minato-ku, Tokyo, Japan) *(MobiSys '24)*. Association for Computing Machinery, New York, NY, USA, 15 pages. https://doi.org/10.1145/3643832.3661867

[5] Qijia Shao, Amy Sniffen, Julien Blanchet, Megan E. Hillis, Xinyu Shi, Themistoklis K. Haris, Jason Liu, Jason Lamberton, Melissa Malzkuhn, Lorna C. Quandt, James Mahoney, David J. M. Kraemer, Xia Zhou, and Devin Balkcom. 2020. Teaching American Sign Language in Mixed Reality. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 4, Article 152 (dec 2020), 27 pages. https://doi.org/10.1145/3432211

[6] Qijia Shao, Li Zhu, Mohsin Ahmed, Korosh Vatanparvar, Migyeong Gwak, Nafiul Rashid, Jungmok Bae, Jilong Kuang, and Alex Gao. 2024. Normalization is All You Need: Robust Full-Range Contactless SpO2 Estimation Across Users. In *ICASSP 2024 - 2024 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. 1646–1650. https://doi.org/10.1109/ICASSP48485.2024.10446435