DESIGN AND DEVELOPMENT OF AN E-TEXTILE USING MUTUAL CAPACITIVE AND INERTIAL SENSOR FUSION FOR UPPER-LIMB POSTURE ESTIMATION

DESIGN AND DEVELOPMENT OF AN E-TEXTILE USING MUTUAL CAPACITIVE AND INERTIAL SENSOR FUSION FOR UPPER-LIMB POSTURE ESTIMATION

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by

Abhinav Komanduri

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Thesis Advisor:
Dr. Alexander H. Nelson
Electrical Engineering and Computer Science

Abstract

Continuous, noninvasive monitoring of upper-limb posture is a critical unmet need in physical rehabilitation, where objective kinematic data can inform therapy decisions, quantify patient recovery, and enable remote monitoring outside of clinical settings. Existing solutions achieve high accuracy only in instrumented laboratories, rendering them unsuitable for the everyday environments where rehabilitation outcomes are ultimately determined. This thesis presents the design, fabrication, and experimental evaluation of a wearable eTextile sensing sleeve for upper-limb posture estimation, combining mutual capacitive sensing with inertial measurement in a fully integrated embedded platform. The sleeve is constructed from a compression-fit athletic fabric spanning the elbow joint. Capacitive signal acquisition is performed by a custom printed circuit board built around the Texas Instruments MSP430FR2676 microcontroller, which leverages the CapTIvate peripheral to digitize mutual capacitance across all four electrode pairs without external analog front-end circuitry. An ESP32 master controller at the wrist aggregates the capacitive data stream from two Bosch BNO055 nine-degree-of-freedom IMUs, one on the upper arm and one on the forearm, and transmits unified telemetry packets to a host computer via Bluetooth Low Energy using a FreeRTOS firmware architecture. This work represents the first integration of eTextile mutual capacitive sensing with dual-segment inertial measurement for upper-limb posture estimation within a single embedded wearable platform, and establishes a functional sensing foundation for future multi-subject validation, multi-degree-of-freedom extension, and clinical deployment in physical rehabilitation monitoring.

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1 Introduction

1.1 Motivation and Problem Statement

Human upper limbs conduct a large amount of coordinated movements in our daily lives, from the motor actions of reaching and lifting to the fine precision of grasping and manipulation. After a major neurological injury or musculoskeletal disorder, the ability to move can become degraded. This is where physical rehabilitation becomes essential to restoring function and independence [2]. Central to effective rehabilitation is the ability to monitor upper-limb posture and movement with sufficient accuracy to assess patient progress, detect compensatory movement patterns, and inform clinical decision-making [3]. Despite decades of research in human motion analysis, the tools available for continuous, real-world upper-limb monitoring remain confined to the clinic and are not accessible.

Currently, optical motion capture systems represent the gold standard for kinematic analysis in laboratory settings, as they can track joint angles and orientations. However, their utility is limited to rooms equipped with calibrated camera arrays, making them quite unrealistic for outpatient treatment, such as in the home, where they are integrated into activities of daily living (ADLs). The infrastructure cost and complexity create a barrier to deployment.

Inertial measurement units (IMUs) are widely adopted wearable alternatives, offering three-axis accelerometry, gyroscopy, and magnetometry in compact, low-cost packages. The IMUs can be attached to limb segments and can estimate orientation and joint angles by inference. Limitations of IMU-based approaches are the integration drift in gyroscopic orientation, ferromagnetic interference in magnetometer readings, and potential discomfort of electronics on soft tissue during movement. Furthermore, standalone IMU systems provide no information about the limb's local deformation or shape [4].

Electronic textiles, or eTextiles, represent a rapidly developing type of wear-

able technology where electronic sensing, actuation, or computation is embedded directly within textile substrates[5]. By integrating conductive materials, such as threads, yarns, inks, and metallic tapes, into garments worn against the body, eTextile systems can contour naturally to the body, distribute sensing across large surface areas, and minimize the obtrusive bulk associated with rigid wearable electronics. Capacitive eTextile sensors, in particular, translate mechanical deformation into measurable changes in electrical capacitance, offering a solution to continuous posture estimation that is inherently form-fitting, garment-integrated, and sensitive to local deformation in ways that inertial sensors are not [6].

The complementary nature of these two sensing modalities, capacitive eTextile sensing and inertial measurement, motivates a multimodal approach to upper-limb posture estimation. Capacitive sensors provide spatially distributed information about limb deformation and surface geometry, while IMUs contribute global orientation context and dynamic movement information. Their fusion has the potential to address the limitations of each modality in isolation, offering a system that is simultaneously wearable, clinically practical, and robust to the ambiguities that beats single-modality approaches.

1.2 Proposed Approach

This thesis presents the design, fabrication, and experimental evaluation of a wearable eTextile sleeve for upper-limb posture estimation. The system presents fusing two complementary modalities of inertial measurement and mutual capacitive sensing modalities within a unified embedded hardware and firmware architecture.

The sleeve is constructed from a form-fitting athletic fabric, chosen for its mechanical features, moisture-wicking properties, and low cost as a base material for wearable applications. Adhesive copper foil electrodes are patterned onto the sleeve to form a mutual capacitive sensing array that responds to changes in arm posture by deforming and altering inter-electrode capacitance. Signal acquisition

from this array is performed by a custom PCB based on the Texas Instruments MSP430FR2676 microcontroller, which incorporates the CapTIvate capacitive-sensing peripheral to enable high-resolution, low-noise mutual-capacitance measurements. Digitized capacitive data is transmitted from the MSP430 to an ESP32 microcontroller via a UART interface.

The ESP32, mounted at the wrist, serves as the master controller for the integrated system. In addition to receiving capacitive data from the MSP430, it interfaces with two BNO055 9-DOF IMUs, one positioned on the upper arm and one on the forearm, to collect accelerometer, gyroscope, and magnetometer data from each limb segment. The ESP32 aggregates these concurrent data streams, packages them into structured data frames, and relays them wirelessly via Bluetooth Low Energy (BLE) to a host mobile app for post-processing and posture estimation. This architecture distributes computation and sensing across a hierarchical embedded system, balancing the specialized capabilities of each processor against the power and communication constraints of a wearable platform.

1.3 Thesis Contributions

The primary contributions of this thesis span the domains of eTextile fabrication, embedded systems design, and multimodal sensor fusion. Specifically, this work makes the following contributions: First, this thesis presents a novel eTextile sleeve design employing copper tape electrodes on an athletic fabric substrate for mutual capacitive posture sensing. The fabrication methodology, electrode geometry, and integration strategy are described in detail, offering a reproducible and low-cost approach to garment-integrated capacitive sensing for the upper limb [7, 8].

Second, this thesis presents a custom embedded hardware and firmware system for multimodal wearable sensing. The MSP430FR2676-based PCB provides dedicated, high-resolution capacitive signal acquisition, while the ESP32-based master architecture supports concurrent IMU data collection and wireless trans-

mission. The firmware design addresses the challenges of timing synchronization, data framing, and real-time communication across multiple embedded processors.

Third, this thesis proposes and characterizes a sensor fusion framework for upper-limb posture estimation that integrates capacitive deformation features with inertial orientation data. The experimental characterization of the capacitive subsystem—including electrode sensitivity, spatial response, and repeatability across arm postures—constitutes the primary experimental result of this work, with the full fusion evaluation pending completion of the inertial data collection protocol.

Collectively, these contributions advance the state of the art in wearable upper-limb monitoring by demonstrating a clinically practical, fully integrated eTextile sensing system that leverages the complementary strengths of capacitive and inertial sensing modalities.

1.4 Thesis Roadmap

The remainder of this thesis is organized as follows. Chapter 2 provides background on upper-limb posture estimation, eTextile sensing principles, mutual capacitance theory, IMU-based orientation estimation, and relevant prior work in sensor fusion for wearable motion analysis. Chapter 3 describes the system architecture and hardware design in detail, covering eTextile sleeve fabrication, the MSP430FR2676 capacitive-sensing PCB, the 9-DOF IMU subsystem, the ESP32 master controller, and the firmware architecture that integrates these components. Chapter 4 reports the experimental results of the system evaluation, focusing on the characterization of the capacitive sensing subsystem and a description of the planned IMU and fusion experiments. It discusses the implications of the experimental findings, the limitations of the current system, and a comparison to related work. Chapter 5 concludes with contributions and directions for future research.

2 Background and Related Work

This chapter provides the necessary background knowledge and an overview of current literature for the work presented.

2.1 Capacitive Sensing and Applications

Capacitance is an object's ability to store electric charge. Two conductive materials with an insulator between them will exhibit capacitance that depends on the distance between them. This phenomenon can be used once realized that the human body acts as a conductor in itself [9].

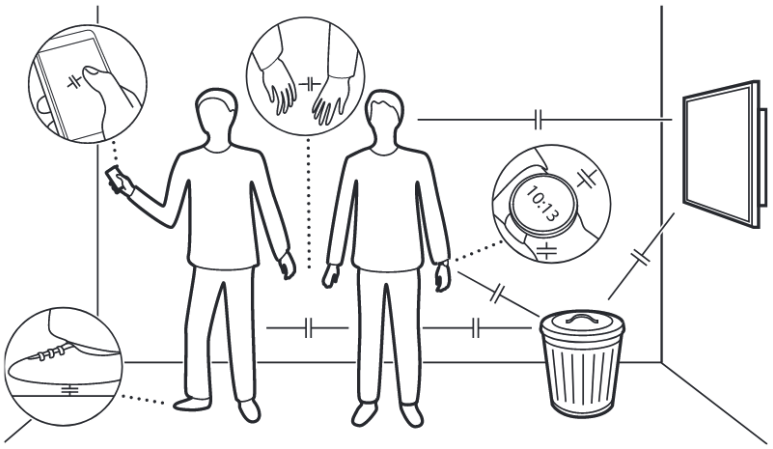


Figure 2.1: Capacitance exists between people, devices, and conductive objects in the environment. By measuring it, capacitive sensors can infer the position and proximity of users and other objects, supporting a range of different applications[1]

.

Capacitive sensing has become such a commonplace technology in our daily lives. Modern-day smartphones and touchscreens are based on capacitive sensing, using our fingers and bodies to shunt charge away as an indication of interaction. It is misconceived that capacitance is solely associated with bought capacitors; natural capacitive coupling occurs in the real world between everything [1] .

Capacitive sensing can be used to estimate many physical properties, such as touch, proximity, or deformation [10].

2.2 Self vs. Mutual Capacitance

Capacitive sensing systems are broadly categorized into self-capacitance and mutual capacitance configurations, each with their own operating principles and trade-offs. In a self-capacitance measurement, a single electrode is driven with an alternating voltage signal and the charge accumulated on that electrode—relative to the surrounding environment—is measured. The self-capacitance of an electrode is sensitive to the proximity of any object with a permittivity or conductivity different from air, including the human body. Self-capacitance implementations are common in proximity sensing and simple touch detection applications. There exists a wide range of self-capacitance and mutual capacitance implementations in human-computer interaction contexts, noting that mutual capacitance configurations offer superior noise immunity and the ability to resolve multi-point interactions that self-capacitance arrays cannot distinguish [1].

In a mutual capacitance measurement, two electrodes are employed: a transmitter (TX) electrode driven by a time-varying excitation signal, and a receiver (RX) electrode held at a reference potential, with the charge induced on it by the TX signal measured. The mutual capacitance between the TX and RX electrodes is determined by the geometry of the electric field coupling between them—specifically, the fraction of the electric field flux emanating from the TX electrode that terminates on the RX electrode rather than dispersing to the surrounding environment. Any dielectric or conductive object introduced into the field path between TX and RX electrodes perturbs this coupling, altering the measured mutual capacitance.

2.3 Upper-Limb Posture Estimation

Proper measurement of upper-limb kinematics is imperative to a broad range of clinical and research applications. In physical rehabilitation, quantitative motion analysis provides therapists and physicians with objective data on patient recovery trajectories, joint range of motion, and compensatory movement strategies that may indicate incomplete recovery and increased injury risk [11] [12] [13]. Conditions such as ischemic attacks, strokes, and traumatic brain injuries all require long-term monitoring of motor movement quality, but clinical practice only relies on inpatient treatments and observation, which can be expensive and time-consuming [14].

There are many solutions for upper-limb motor tracking, including electromyography, optical video capture, inertial tracking, and more. Each of these has varying degrees of effectiveness and is often expensive and not akin to activities of daily living. Capacitive sensing promises an easy-to-integrate solution [1] [15].

2.4 Capacitive Sensing in Loose-Fitted Clothing

MoCaPose, developed by Zhou et al., is among the most directly relevant prior systems to the present work [16]. MoCaPose integrates textile capacitive sensors into loose-fitting smart garments and employs machine learning to map multi-channel self-capacitive signals to estimates of body posture. The system demonstrated that capacitive sensing in garments could capture meaningful postural information even when the garment did not maintain consistent contact with the underlying body surface—a significant finding given the practical challenges of garment fit variability. However, the loose-fitting nature of the garments in MoCaPose introduces substantial variability in the electrode-skin distance and contact geometry across wearers and postures, which the authors address through subject-specific calibration and data-driven modeling. The present work differs by employing a form-fitting athletic sleeve that uses mutual capacitance principles

to maintain consistent electrode proximity to the limb surface, thereby reducing fit-induced variability and enabling a more direct physical interpretation of capacitance changes in terms of limb deformation.

SeamPose, presented by Yu et al., takes a distinctive approach to garment-integrated capacitive sensing by repurposing shirt seams as capacitive electrodes for upper-body pose tracking [17]. By exploiting existing garment seams rather than adding discrete electrode structures, SeamPose minimizes the impact of sensor integration on garment aesthetics and mechanical properties. The system demonstrated the feasibility of continuous upper-body pose estimation from seam-integrated capacitive signals, achieving accuracy sufficient to distinguish a meaningful vocabulary of upper-body configurations. SeamPose illustrates the importance of electrode placement strategy in determining the postural information content of capacitive signals: seam locations, while mechanically natural, constrain the spatial distribution of sensing to predetermined garment construction lines. The present work employs a deliberate electrode layout on the upper and lower arms, specifically designed to capture deformation patterns associated with elbow flexion and forearm rotation, providing greater spatial coverage and design flexibility than seam-constrained approaches.

MobilePoser is a real-time full-body motion capture system that leverages commodity consumer devices users already wear or carry, such as smartphones, smartwatches, and wireless earbuds [18]. Using a sparse and dynamic set of just one to three low-fidelity IMUs, the system addresses the highly under-constrained challenge of pose and global translation estimation. It employs a multi-stage deep neural network that uses bidirectional LSTMs to predict joint kinematics, followed by a physics-based motion optimizer to resolve spatiotemporal inconsistencies such as foot-skating or joint penetration. For global translation estimation, it uses a hybrid approach that fuses a foot-ground contact estimator with a direct neural network velocity regressor. Running entirely on-device at 60 frames per second, MobilePoser achieves state-of-the-art accuracy in sparse consumer-device configurations, making it highly suitable for everyday, unconstrained applications such as

fitness tracking, gaming, and indoor navigation.

Flexible Inertial Poser (FIP) is a hybrid motion capture system that integrates four IMUs and two flex sensors into comfortable, loose-fitting daily clothing [19]. To overcome the significant tracking challenges caused by sensor shifting in loose garments, FIP introduces three specialized components: a Displacement Latent Diffusion Model (DLDM) that synthesizes realistic IMU vibration data to train the system to handle real-time fabric displacement, a Physics-informed Calibrator (PIC) that corrects primary flex sensor misalignment through a single vertical elbow bend, and a Pose Fusion Predictor (PFP) that merges the multi-modal sensor readings with a specific focus on elbow rotation. By combining the global spatial awareness of IMUs with the direct joint-angle measurements of flexible sensors, the system significantly enhances upper-limb tracking. Running at 60 frames per second, FIP outperforms state-of-the-art IMU-only systems, demonstrating a 19.5% reduction in angular error and a 26.4% improvement in elbow tracking accuracy, paving the way for ubiquitous motion capture in home rehabilitation and AR/VR.

TouchPose by Ahuja et al. reconstructs full 3D hand poses from the low-resolution capacitive images captured by commodity touchscreens. The system utilizes a multi-task Convolutional Neural Network that simultaneously predicts the 3D hand skeleton, estimates a depth map, and classifies whether the touch is a fingertip or whole hand. By operating on partial observations, it can infer joint positions that lie outside the touch sensor's physical volume. Evaluated on a custom dataset, TouchPose achieves an average end-point error of 21.8 mm per joint, allowing developers to use complex 3D hand poses for advanced touchscreen interactions [20].

TrackPose by He et al. focuses on providing highly stable and accurate finger pose estimation on capacitive touchscreens. To process continuous capacitive image sequences, it employs a time-series deep neural network with a self-attention mechanism, along with a specialized tracking loss function that forces the model to forecast smoother finger movements. Furthermore, it includes a short mobile registration app that captures custom user data without external optical devices,

accommodating individual differences in finger shape. These methods combined reduce overall angle estimation error by 33% and decrease sequential instability by 62% [21].

Capacitivo by Wu et al. is a contact-based sensing technique built into interactive fabrics that recognizes non-metallic everyday objects, such as fruits, liquids, and plastics. The prototype uses a 12x12 grid of diamond-shaped conductive fabric electrodes to measure both the self-capacitance and mutual capacitance footprints of an object resting on the textile. By processing this data through a Random Forest machine learning classifier, the system achieved a 94.5% real-time accuracy across 20 distinct objects. This allows everyday fabrics to become context-aware, enabling applications like a smart tablecloth that reminds users of forgotten items or suggests recipes based on ingredients placed on it [22].

2.5 IMUs for Motion Tracking

A nine-degree-of-freedom IMU integrates three distinct sensing modalities on a common platform: a three-axis accelerometer, a three-axis gyroscope, and a three-axis magnetometer. Each modality contributes information to estimating the sensor's orientation in 3D space. The accelerometer measures the specific force acting on the sensor package—the vector sum of linear acceleration and gravitational acceleration—expressed in the sensor body frame. In the absence of linear acceleration, the accelerometer output aligns with the local gravitational vector, providing a reference for the pitch and roll angles of the sensor frame relative to the Earth frame. The gyroscope measures the angular velocity of the sensor body frame, enabling orientation to be propagated forward in time by integrating the measured angular rate. The magnetometer measures the local magnetic field vector, which provides a reference for the yaw angle of the sensor frame relative to north [4].

2.6 Prior Lab Work in Capacitive Sensing

Prior work from Nelson et al. presents an adaptive, non-contact proximity gesture recognition system designed to assist individuals with severe upper-extremity mobility impairments, such as spinal cord injuries [23]. To avoid the skin-friction injuries associated with traditional touch-based or rigid wearable devices, the researchers developed flexible, lightweight textile capacitive sensor arrays that can be seamlessly integrated into everyday fabrics such as clothing, pillow covers, and bedsheets. The system tracks hand movements in the 3D space above the sensor plates and fuses this spatial data with a wrist-worn accelerometer to automatically adapt to any rotation or displacement of the fabric sensor patch. By processing raw capacitance and inertial data using Dynamic Time Warping (DTW) and Hidden Markov Model (HMM) algorithms, the system successfully translates tracked hand positions into complex alphanumeric gestures with an average accuracy of 99%, all while requiring minimal user training.

The prior lab work of Liu et al. proposes a low-cost, portable rehabilitation assistant system designed for individuals recovering from upper-extremity motor impairments caused by brain injuries, spinal cord injuries, or strokes [24]. The core of the system is a rehabilitation activity board overlaid with a 4x5 mutual capacitive sensor array constructed from transparent Indium Tin Oxide (ITO) films arranged in a single-layer diamond pattern. This array continuously quantifies patients' hand motions, detecting proximity, touch, and complex multi-touch trajectories such as swipe gestures. Alongside the capacitive array, a 3-axis accelerometer monitors the board's inclination, which is critical because varying slopes can significantly affect a patient's motor quality during exercises. The combined sensor data is processed by microcontrollers and transmitted via Bluetooth to a Raspberry Pi, which hosts a web interface that provides real-time visual feedback of the hand positions and board slope. Ultimately, the researchers aim to use this system to automatically detect a patient's recovery progress by analyzing the physical attributes of their motions, which could reduce both the cost of rehabilitation and

the manual workload for medical professionals.

Finally, the work done by Komanduri et al. presents a system designed to enhance the spatial resolution of Capacitive Sensor Arrays (CSAs) for ubiquitous sensing applications, specifically to improve spatial awareness in soft robotics for safer human-robot interaction and delicate tasks like fragile crop harvesting [25][26]. Because individual microcontrollers, such as the Texas Instruments MSP430FR2676, are typically limited to supporting up to 64 mutual-capacitive sensors (an 8x8 grid), the researchers propose a novel architecture that daisy-chains multiple microcontrollers using the I2C serial protocol [27]. In this configuration, one board acts as the central controller, while additional connected boards operate as peripherals, theoretically allowing the system to scale up to 256 sensors. The researchers successfully demonstrated a rapid prototype that linked two 8x8 CSAs to achieve a 128-sensor grid, transmitting the combined spatial data to a data collector via the UART protocol. To further advance this technology for high-resolution robot skins, the authors plan to transition the prototype to custom Printed Circuit Boards (PCBs) and use Field Programmable Gate Arrays (FPGAs) to meet the rapid processing speeds required for larger, proximity-based data packets [28].

2.7 Limitations and Research Gap

Despite the rapid adoption of capacitive sensing, significant technical limitations remain. Capacitive sensors suffer from instability and are highly sensitive to variations in electrical grounding and environmental electromagnetic noise. The durability of textile-based capacitive traces against mechanical fatigue and repeated wash cycles also remains an ongoing materials science challenge. From an algorithmic standpoint, while models can simulate or calibrate initial sensor displacements on loose clothing, real-time correction of massive, unpredictable displacements—such as those caused by forceful tugging during vigorous movement—remains an unsolved challenge. Finally, there is a notable research gap in integrating high-resolution mutual capacitance grids with IMU sensor fusion

directly into everyday smart garments, as current prototypes typically limit themselves to simpler single-ended capacitive modes to avoid overwhelming textile routing complexity. This work attempts to address this gap while also showing how this approach does not require a strong ground reference.

3 Methodology

This section provides an overview of the hardware and firmware architecture for the sleeve. The system spans three main subsystems: the garment embedded with copper foil electrode arrays, the custom MSP430-based capacitive sensing printed circuit board, and the ESP32 controller that aggregates the capacitive and inertial data and relays over Bluetooth to a device. Section 3.1 presents a top-level overview of the design requirements. Section 3.2 details the sleeve fabrication process, including material choice, electrode topology, and system integration. Section 3.3 shows the custom capacitive PCB and the CapTIvate peripheral. Section 3.4 covers the BNO055 9-DoF IMU subsystem and its fusion into the overall sensing system. Section 3.5 describes the ESP32 controller device and the roles of data aggregation and BLE transmission. Section 3.6 shows the firmware architecture for the MSP430 and ESP32, including task scheduling, packet framing, and synchronization protocols.

3.1 System Overview

The system is organized in two parts, illustrated in Figure 3.1. At the first tier, the MSP430FR2676 microcontroller, mounted on a custom PCB integrated into the sleeve, acquires data from the four-channel mutual-capacitive sensor array. The MSP430 operates autonomously, relying on the CapTIvate scan loop and streaming digitized raw count measurements to the second tier via UART serial. At the second tier, the ESP32 microcontroller, located at the wrist, acts as the system controller. It receives the capacitive data stream from the MSP430 and simultaneously polls two BNO055 9-DOF IMUs over a shared I^2C bus: one IMU mounted on the upper arm and one on the forearm. The ESP32 merges these three concurrent data streams into structured packets, which are transmitted over Bluetooth Low Energy (BLE) to an Android mobile application running the post-processing and posture estimation pipeline.

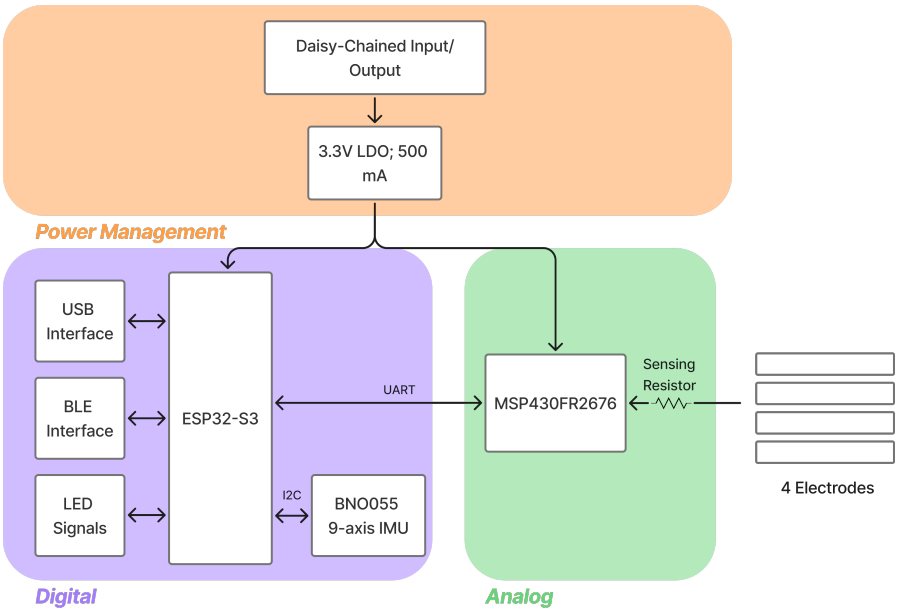


Figure 3.1: Block diagram overview of the architecture of multi-modal capacitive inertial acquisition.

3.1.1 Design Requirements

The requirements were guided by function and aesthetic needs derived from the target application of upper-limb posture estimation for physical rehabilitation monitoring. The system must acquire mutual capacitance from all four electrode pairs on the sleeve at a rate sufficient to capture the dynamics of voluntary movement, defined as the minimum sample rate of 50 Hz per channel. It must also simultaneously acquire inertial data from both IMUs at a comparable rate. The system should transmit all streams to the host with minimal latency for real-time visualization

For comfort and wearability, the sensing electronics must be compact and lightweight enough to be worn on the arm without impeding natural movement. The PCB also cannot be located at pressure points or have constraints that would alter the sleeve's natural deformation. The system will be battery-powered. Finally, the eTextile sleeve must maintain electrode contact and be provided with a

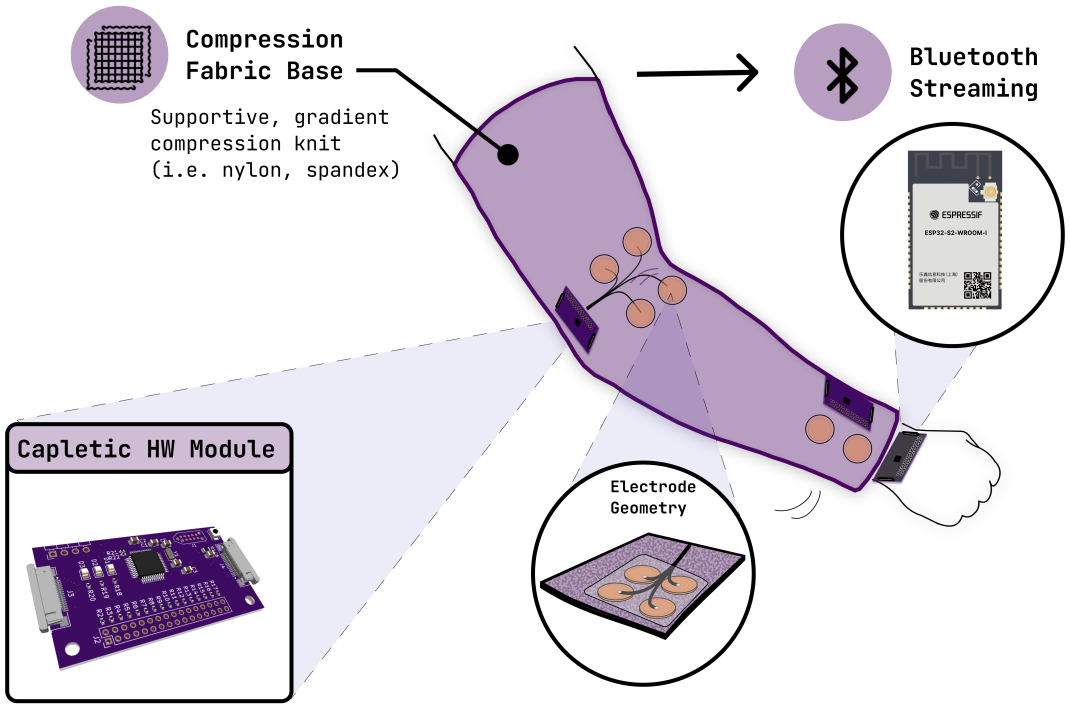


Figure 3.2: Sleeve concept diagram with compression fabric and Bluetooth streaming.

stable, large human-body-model ground plane.

3.2 eTextile Sleeve Fabrication

The mechanical and electrical performance of an eTextile capacitive sensor is dependent on the properties of the base textile material. For the present system, a commercial-off-the-shelf compression athletic sleeve was selected as the substrate. The sleeve is composed of a spandex-polyester blend fabric that provides high elastic compliance, enabling it to conform tightly to the arm surface across a wide range of limb sizes and joint angles, while maintaining sufficient structural integrity to hold electrode structures in stable positional registration relative to the underlying anatomy. The compression fit of the athletic fabric is essential to the sensing strategy: by maintaining consistent contact between the copper tape

electrodes and the arm surface, it minimizes the variability in proximity that was identified as a limitation of loose-fitting eTextile systems such as MoCaPose.

The substrate's thickness and dielectric properties influence both the baseline mutual capacitance of the electrode array and the magnitude of deformation-induced capacitance changes. The spandex-polyester blend exhibits a relative permittivity in the range typical of synthetic polymer textiles, sufficient to support measurable inter-electrode coupling at the electrode dimensions and separations employed in this design. The fabric surface is smooth and consistent in texture, supporting reliable adhesion of the copper tape electrode structures without the fiber-scale roughness that can introduce delamination stress concentrations under repeated flexion-extension cycling. The electrodes were also laminated to add a dielectric layer and to ensure mechanical rigidity.

The electrode array consists of four copper tape strips arranged around the arm, spanning the region from the mid-upper arm to the mid-forearm and crossing the elbow joint. Each electrode strip measures 1 cm in width and 10 cm in length, oriented perpendicular to the long axis of the arm so as to surround the limb. The four strips are arranged in an alternating transmitter-receiver (TX-RX-TX-RX) pattern along the axial direction of the sleeve, with uniform inter-strip spacing selected to balance inter-electrode coupling strength against crosstalk suppression.

This electrode configuration produces three adjacent TX-RX mutual capacitance pairs along the axial direction of the sleeve: between strips 1 and 2 (TX1–RX1), between strips 2 and 3 (RX2–TX2), and between strips 3 and 4 (TX2–RX2). The orientation of each strip means that the electric field coupling between adjacent TX and RX strips is primarily axially directed—spanning the inter-strip gap along the arm length—and is therefore sensitive to elongation and compression of the sleeve, which correspond to elbow flexion and extension respectively. As the elbow flexes, the anterior surface of the sleeve compresses while the posterior surface elongates, producing differential changes in the mutual capacitance of strip pairs on the anterior and posterior aspects of the arm. This differential response is the primary physical mechanism by which the system de-

termines elbow joint angle in the capacitive signal.

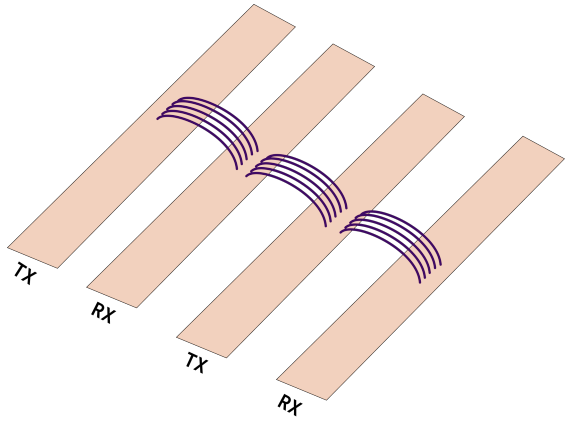


Figure 3.3: Mutual capacitance coupling between electrodes of TX and RX. Shows three unique pairings that indicate movement.

3.3 Capacitive Sensing Hardware

3.3.1 Microcontroller Selection

The Texas Instruments MSP430FR2676 was selected as the dedicated capacitive sensing processor for this system based on its integration of the CapTIvate capacitive sensing peripheral, a hardware block specifically designed for high-resolution, low-noise capacitive measurement without the need for external analog front-end circuitry. The CapTIvate peripheral implements a charge-transfer measurement architecture that directly digitizes the charge accumulated on sensing electrodes, offering inherent noise rejection through oversampling and on-chip digital filtering. The MSP430FR2676 operates at 3.3V logic level and features ultra-low-power operating modes that allow the CapTIvate peripheral to scan the electrode array while the CPU remains in a low-power sleep state, waking only to process and transmit completed scan results.

3.3.2 Custom PCB Design

A custom two-layer PCB was designed from scratch to host the MSP430FR2676 and the supporting circuitry required for the system. The PCB design encompasses power regulation, crystal oscillator for accurate timing, UART interface circuitry for communication with the ESP32, and the electrode connector interface through which the four capacitive electrode leads from the sleeve are routed to the CapTIvate peripheral inputs. The top of the board features an FFC connector with common lines (I2C, UART, Power) for the ability to daisy-chain. The PCB form factor was constrained to a compact footprint compatible with integration into the sleeve assembly.

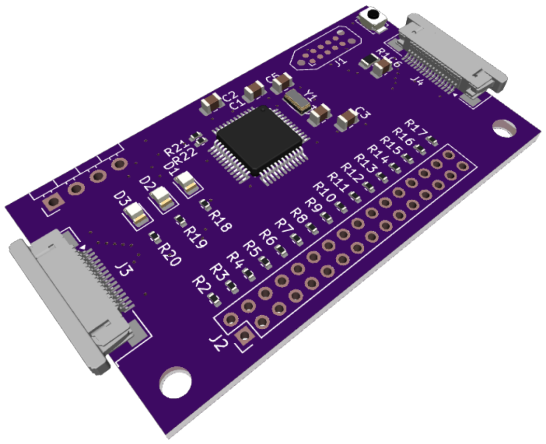


Figure 3.4: PCB of custom MSP430FR2676 board with FFC connectors and 1.25” capacitive sensor inputs.

The power supply of the PCB accepts an input voltage of up to 5V from the FFC connector and provides a regulated 3.3 V rail to the MSP430FR2676 and associated peripherals. Decoupling capacitors are placed in close proximity to the VCC pins of the microcontroller in accordance with the layout recommendations in the MSP430FR2676 datasheet, minimizing supply noise that could couple into the sensitive capacitive measurement circuitry. The CapTIvate electrode traces on the PCB are routed with particular care to minimize parasitic coupling to

adjacent signal lines and to maintain consistent trace lengths between the electrode connector and the CapTIvate peripheral inputs, as trace parasitic capacitance directly adds to the electrode baseline capacitance and must remain stable across operating temperature and mechanical deformation [27].

3.3.3 CapTIvate Peripheral Configuration

The CapTIvate peripheral of the MSP430FR2676 was configured for mutual capacitance measurement across the four electrode strips of the sleeve array. In the mutual capacitance measurement mode, CapTIvate drives a designated set of TX electrode pins with an excitation signal and simultaneously measures the charge induced on one or more designated RX electrode pins, producing a digital raw count value proportional to the mutual capacitance between each TX-RX pair. The peripheral supports flexible electrode assignment through software configuration, allowing the TX and RX roles of individual pins to be defined and modified without hardware changes. For this system, the four electrode strips are assigned to the CapTIvate peripheral inputs such that the two TX strips (strips 1 and 3) are connected to transmitter-configured pins and the two RX strips (strips 2 and 4) are connected to receiver-configured pins. The peripheral is configured to perform a sequential scan of all active TX-RX pairs in each measurement cycle, producing a complete set of mutual capacitance counts for the full electrode array at the conclusion of each scan. The oversampling ratio and conversion gain of the CapTIvate peripheral are set to maximize measurement resolution within the timing budget imposed by the target sampling rate. The internal digital filter of the CapTIvate peripheral is enabled to suppress high-frequency noise contributions from switching transients and electromagnetic interference, producing a stable, low-noise output count for each electrode pair.

3.3.4 UART Bridge to ESP32

The capacitance measurement results from the CapTIvate peripheral are read by the CPU at the end of each scan cycle and formatted into a binary data packet for transmission to the ESP32 master controller via the Universal Asynchronous Receiver-Transmitter (UART) interface. The UART is configured at a baud rate of 115200 bps, which provides sufficient throughput to transmit all four capacitance count values—each represented as a 16-bit unsigned integer—along with a frame synchronization header and checksum byte, at the target sampling rate of 50 Hz per channel. The frame structure includes a fixed-byte start-of-frame marker to enable the ESP32 receiver to re-synchronize to the data stream in the event of a communication disruption.

3.4 IMU Subsystem

3.4.1 Sensor Selection and Capabilities

The BNO055 from Bosch Sensortech was chosen as the 9-DoF inertial measurement unit for both arm segament position tracking. The BNO055 is an integrated circuit package that integrates triaxial accelerometer, triaxial gyroscope, and triaxial geomagnetic sensor on a single chip. The chip executes fusion of data that outputs calibrated, fused oreientaiton estimates directly in the form o f Euler angles or unit quaternions instead of raw data.

The BNO055 communicates with the ESP32 via the I^2C serial interface, supporting clock frequencies up to 400 kHz. The device supports two selectable I^2C addresses through a hardware address pin, enabling two BNO055 units to share a single I^2C bus without address conflict—a feature that directly enables the dual-IMU configuration employed in this system. The BNO055 operates from a 3.3 V supply. An off-the-self breakout module was purchased for integration into the sleeve.

3.4.2 Placement and Mounting

Two BNO055 IMUs are integrated into the sleeve: one mounted on the upper arm and one on the forearm. The upper-arm IMU is positioned in the mid-upper arm, midway between the shoulder and elbow joints secured using sewing and hot glue. The forearm IMU is positioned on the surface of the mid-forearm, midway between the elbow and wrist joints, and secured using the same mounting method. These placement locations were selected to minimize soft tissue motion artifact.

3.4.3 I^2C Bus Configuration

Both BNO055 units are connected to a single I^2C bus hosted by the ESP32 master controller. The two sensors are assigned distinct I^2C addresses by configuring the address selection pin of each device to a different logic level: the upper-arm BNO055 is assigned the primary address (0x28) and the forearm BNO055 is assigned the secondary address (0x29). The I^2C bus is operated at 400 kHz Fast Mode, with pull-up resistors on both SDA and SCL lines sized to provide the required edge slew rate at the bus capacitance presented by the two sensor loads and PCB trace lengths. The ESP32 polls each BNO055 sequentially by asserting the respective I^2C address and reading the fusion output registers, which provide the current orientation quaternion and calibration status byte in a single burst read transaction.

3.5 ESP32 Controller Device

3.5.1 Microcontroller Selection

The ESP32 system-on-chip microcontroller serves as the master controller of the integrated sensing system. Its primary responsibilities are to receive the capacitive data stream from the MSP430FR2676 over UART, to poll both BNO055 IMUs over I^2C, to merge these concurrent data streams into coherent, timestamped

packets, and to transmit the aggregated data to the host computer via Bluetooth Low Energy. The Espressif ESP32 was selected for this role based on its combination of dual-core processing capability, integrated BLE and Wi-Fi radio, rich peripheral set including multiple hardware UART and I²C controllers, and wide availability in compact module form factors suited to wrist-mounted wearable enclosures.

The ESP32-S3 WROOM module used in this system integrates the ESP32 SoC with an onboard PCB antenna, a 8 MB flash memory, and the required RF matching network, providing a self-contained wireless communication platform that requires minimal external circuitry. The module is powered from the system battery through a 3.3 V low-dropout regulator, and its GPIO pins are used to interface with the MSP430 UART lines, the I²C bus shared by the two BNO055 IMUs, and any status indicator LEDs included in the module.

3.5.2 Data Collection and Transmission

The ESP32 merges the capacitive and inertial data streams into a unified packet that is transmitted to the host over BLE at each sampling interval. Each packet contains: a specialized header derived from the ESP32 internal timer, four 16-bit mutual capacitance count values received from the MSP430, four 16-bit quaternion components (w, x, y, z) from the upper-arm BNO055, four 16-bit quaternion components from the forearm BNO055, two 8-bit calibration status bytes (one per BNO055), and a trailing 16-bit CRC for packet integrity verification. The total packet length is 38 bytes in the connection-oriented Generic Attribute Profile (GATT) configuration used for data transmission.

Data transmission to the host device is implemented using the Bluetooth Low Energy GATT protocol, with the ESP32 operating as a BLE peripheral advertising a custom GATT service containing a single notification-enabled characteristic. The host device, running a Python data acquisition script, connects to the ESP32 as a BLE central device and enables notifications on the data characteris-

tic, after which the ESP32 transmits one telemetry packet per sampling interval as a BLE notification. The BLE connection parameters, specifically the connection interval and slave latency, are configured to support the target sampling rate while minimizing radio duty cycle and thereby reducing average current draw from the system battery.

3.6 Firmware Development

3.6.1 MSP430 Firmware

The firmware running on the MSP430FR2676 is structured as a bare-metal application organized around the CapTIvate library provided by Texas Instruments as part of the MSP430 CapTIvate Design Center software framework. The main application loop initializes the CapTIvate peripheral with the previously described electrode configuration, then enters a low-power mode, delegating scan execution to the CapTIvate hardware. The CapTIvate peripheral operates autonomously, executing the configured scan sequence at the programmed interval and asserting an end-of-conversion interrupt upon completion of each full scan cycle. The end-of-conversion interrupt service routine reads the digital count values for all four mutual capacitance pairs from the CapTIvate result registers, assembles the fixed-length binary frame comprising the start-of-frame byte, four 16-bit count values in big-endian byte order, and a CRC-8 checksum computed over the data payload, and initiates a UART transmission to the ESP32. The firmware is written in C using the TI Code Composer Studio development environment and compiled with the MSP430 compiler.

3.6.2 ESP32 Firmware

The ESP32 firmware is implemented using the Espressif IoT Development Framework (ESP-IDF) and is structured as a set of FreeRTOS tasks, each responsible for a distinct system function. This task-based architecture allows the ESP32 dual-core processor to execute communication and processing functions concur-

rently, improving throughput and reducing end-to-end latency relative to a polling architecture.

UART Receive Task: A task runs on Core 0 of the ESP32 and monitors the UART peripheral connected to the MSP430FR2676 for incoming data frames. Upon detection of the start-of-frame bit, the task reads the remainder of the fixed-length frame into a receive buffer, validates the CRC-8 checksum, and, if the frame is valid, posts the four capacitance count values to a queue shared with the packet assembly task. Invalid frames are discarded, and a software counter is incremented to track the frame error rate for diagnostic purposes.

IMU Poll Task: A second task runs on Core 0 and is responsible for polling both BNO055 IMUs over the I^2C bus. The IMU poll task sequentially addresses each BNO055 via I^2C, reads the quaternion output registers and calibration status byte for each sensor, and posts the results to the packet assembly queue.

Bluetooth Transmission: A task runs on Core 1 and waits on the packet assembly queue for a complete set of capacitive and inertial data. Upon receiving data from both the UART receive task and the IMU poll task, this task assembles the 38-byte packet and computes the 16-bit CRC over the assembled payload, and calls the BLE stack notification API to transmit the packet to the connected host.

3.7 Sensor Fusion and Pose Estimation

The hardware and firmware architecture described in the preceding sections is designed to support a sensor-fusion pipeline that combines capacitive and inertial data streams to produce a unified estimate of elbow flexion angle. While full implementation of this pipeline is deferred to future work, this section describes the intended approach to establish the algorithmic direction of the system [29].

For the capacitive modality, the raw four-channel CapTIvate count vector will be baseline-corrected by subtracting a reference measurement acquired at 0°

of elbow flexion, and the resulting differential vector will be mapped to a flexion-angle estimate via a polynomial regression model fitted to labeled data collected at known reference postures as ground truth. For the inertial modality, the BNO055 on-chip fusion output provides a calibrated orientation quaternion for each limb segment; the elbow flexion angle is derived from the relative quaternion between the two sensor frames, projected onto the anatomical flexion axis identified through a functional calibration procedure.

The two modality-specific angle estimates will be combined using a confidence-weighted fusion scheme, in which each estimate is assigned a weight proportional to its instantaneous reliability. The capacitive confidence score will be derived from the residual between the observed count vector and the regression model's predicted value at the estimated angle; the IMU confidence score will be taken directly from the BNO055 system calibration status register, which reports self-assessed fusion quality on a 0–3 scale. The normalized weighted average of the two estimates constitutes the fused output angle, accompanied by a joint confidence metric that reflects the combined reliability of both modalities. This approach is expected to leverage the complementary failure modes of the two sensing modalities—the capacitive system is immune to magnetic disturbance while the IMU is unaffected by garment displacement—yielding a fused estimate that is more robust than either source alone [30].

4 Experimental Evaluations and Discussion

This chapter presents the experimental evaluation of the integrated eTextile posture estimation system. Section 4.1 describes the experimental setup and reports results for both the capacitive sensing and inertial measurement subsystems. Section 4.2 discusses the implications of these findings, the observed limitations of the system, and the path toward full sensor fusion.

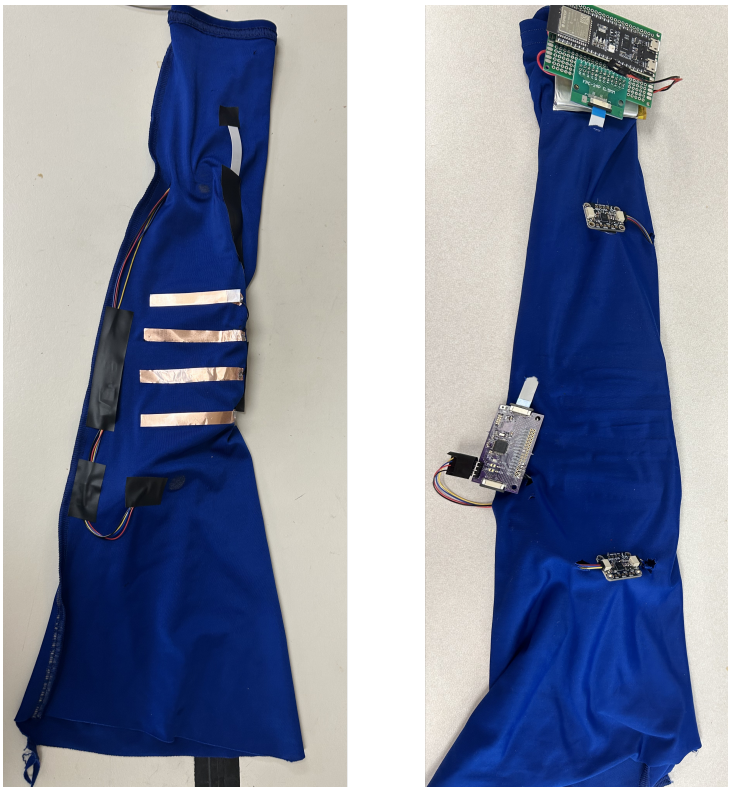


Figure 4.1: Layer 1 (left) with electrodes and hidden wires, and Layer 2 (right) with sensors and computing devices.

4.1 Setup and Results

All experiments were conducted on a single subject—the thesis author, with the eTextile sleeve donned on the dominant arm. Prior to each session, the

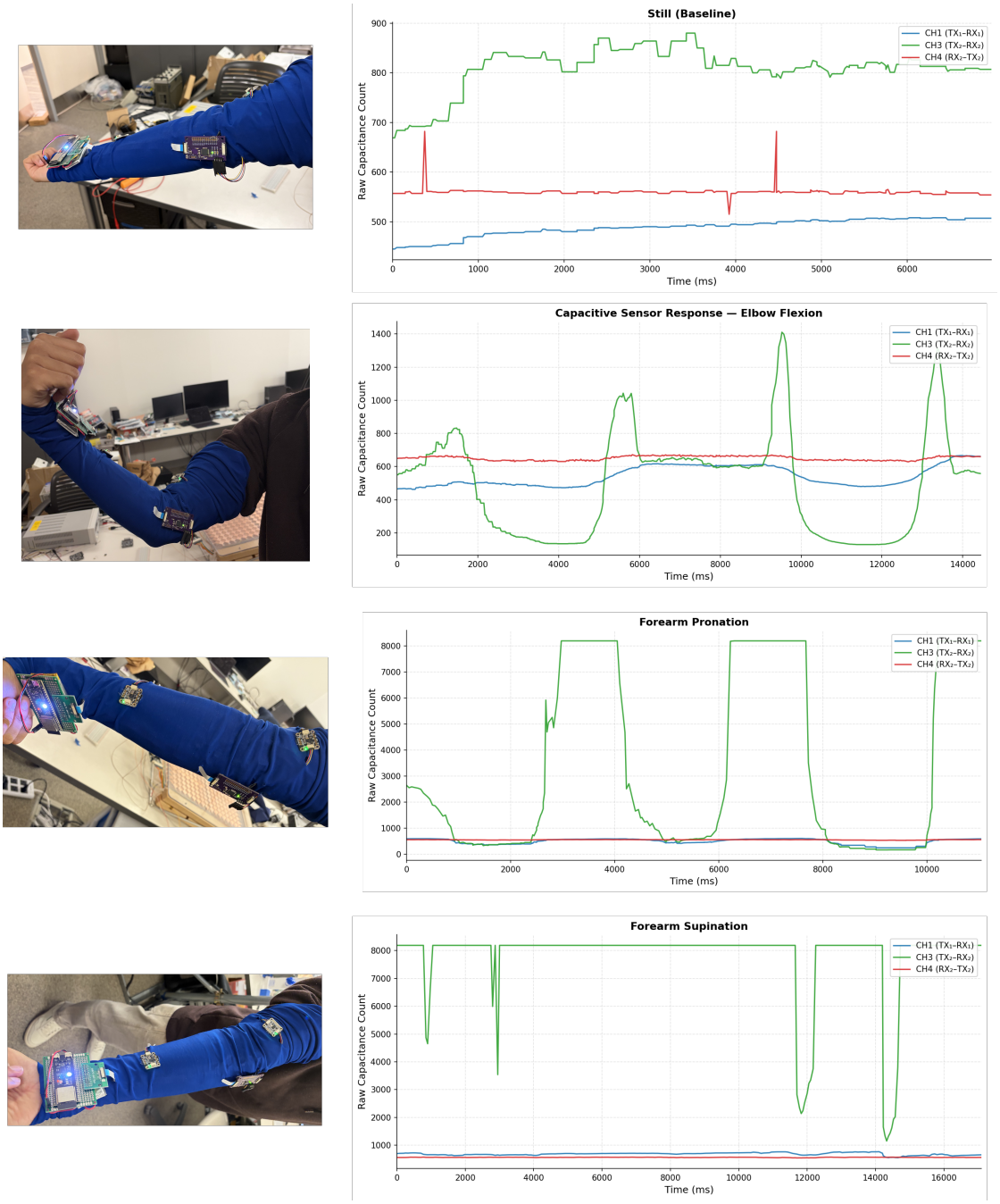


Figure 4.2: Capacitive channel data for four distinct motions (flexions and sup/pronations) while being worn.

sleeve was positioned so that the electrode array spanned the elbow joint, with the proximal TX strip located on the mid-upper arm and the distal RX strip on the mid-forearm. Consistent positioning across sessions was ensured by aligning a reference mark on the sleeve. The two BNO055 IMUs were mounted on the lateral surface of the mid-upper arm and the dorsal surface of the mid-forearm, respectively, secured with medical-grade double-sided adhesive tape, and verified to be rigidly coupled to each segment prior to data collection.

Following donning, a thirty-second stabilization period was observed before data collection to allow the CapTIvate peripheral to complete its offset calibration and the BNO055 sensors to achieve full system calibration status across all four internal subsystems (system, gyroscope, accelerometer, and magnetometer). The baseline count vector was then acquired at full elbow extension by averaging fifty consecutive scan frames.

Four motions were evaluated to characterize the response of both sensing subsystems across the primary degrees of freedom of the upper limb: elbow flexion, elbow extension, forearm pronation, and forearm supination. Each motion was performed as a controlled dynamic sweep—moving smoothly from the neutral position through the full range of the motion and returning, while continuous data were recorded through the complete BLE pipeline at the nominal 50 Hz sampling rate.

Figure 4.2 shows how different movements correlate with the capacitive data raw counts over time in milliseconds.

4.2 Discussion of Results

The capacitive results show that the sleeve produces interpretable data and responses across each of the four evaluated upper-limb motions. The response to elbow flexion confirms that the geometry can capture the motion and is well attached to deform. As the sensors get closer together, the raw counts decrease, which is consistent with theory. These findings are consistent with the behavior

reported in prior eTextile capacitive sensing work. The spatially graded sensitivity across channels proximal and distal to the joint axis echoes observations in MoCaPose.

The BNO055 inertial subsystem was successfully integrated into the ESP32 master controller and verified to be operational, with both IMUs powering on and communicating over the I^2C bus without error. Full experimental characterization of the IMU response, including orientation accuracy, joint-angle estimation, and sensor fusion with the capacitive array, remains as planned future work.

5 Conclusion and Future Work

This thesis presented the design, fabrication, and experimental evaluation of an eTextile-based sensing platform for upper-limb posture estimation, integrating mutual capacitive sensing with dual-segment inertial measurement within a fully embedded, wirelessly connected wearable system. This chapter summarizes the contributions of the work, reflects on the significance of the results, and identifies concrete directions for future development.

5.1 Summary of Contributions

This thesis made three primary contributions to the field of wearable upper-limb sensing.

The first contribution is the design and fabrication of a novel eTextile sensing sleeve for upper-limb posture estimation. The sleeve integrates four copper tape electrodes arranged in an alternating TX-RX-TX-RX pattern on a compression-fit athletic substrate, producing a mutual capacitive sensing array that responds to elbow flexion-extension and forearm pronation-supination through distinct, physically interpretable deformation signatures. The fabrication using commercially available materials demonstrates a low-cost, reproducible approach to garment-integrated capacitive sensing compatible with the mechanical demands of upper-limb wearable applications.

The second contribution is a custom embedded hardware and firmware system for multimodal wearable sensing. The MSP430FR2676-based PCB, designed from scratch, provides dedicated high-resolution mutual capacitance acquisition via the CapTIvate peripheral without external analog front-end circuitry, and transmits digitized results to an ESP32 master controller. The ESP32 aggregates the capacitive stream with quaternion orientation data from two BNO055 9-DOF IMUs over I^2C, packages all data into structured 38-byte telemetry frames, and delivers them to a host computer via Bluetooth Low Energy at 50 Hz. The FreeRTOS

task architecture on the ESP32 isolates sensor acquisition from BLE transmission across the two processor cores, ensuring deterministic timing and preventing radio latency from disrupting the sensor sampling.

The third contribution is the experimental characterization of the integrated sensing platform across four upper-limb motions—elbow flexion, elbow extension, forearm pronation, and forearm supination demonstrating that the capacitive array produces monotonic, spatially graded, and motion-discriminative responses for each evaluated condition, and that the dual-IMU inertial subsystem produces physically consistent, well-separated gravity vector projections during elbow flexion-extension that are indicative of correct relative orientation sensing between limb segments. Together, these results validate the functional operation of both sensing subsystems.

5.2 Significance of the Work

The system presented in this thesis addresses a genuine unmet need in wearable upper-limb sensing. Existing approaches—optical motion capture, rigid-body-mounted IMU systems, and electromyography each impose constraints on wearability, environment, or signal interpretability that limit their suitability for continuous clinical monitoring outside the laboratory. The eTextile sleeve developed here is form-fitting, low-profile, and constructed from materials compatible with extended wear during activities of daily living, while the hierarchical embedded architecture provides wireless, real-time data delivery without tethered connections to laboratory infrastructure.

The fusion of eTextile mutual capacitive sensing with dual-segment inertial measurement represents a novel combination of modalities that has not previously been demonstrated for upper-limb posture estimation. As identified in the literature review, prior eTextile posture sensing systems, including MoCaPose [3] and SeamPose [6], rely exclusively on capacitive or resistive textile sensing without inertial augmentation, whereas IMU-based systems do not exploit the complemen-

tary deformation information provided by a garment-integrated electrode array. The present work demonstrates that these two modalities can be co-integrated in a single wearable platform and that each responds to the target degrees of freedom through independent physical mechanisms, providing the sensing diversity necessary for robust, confidence-aware fusion.

The observation that the four-channel capacitive array produces a qualitatively distinct torsional response signature during forearm pronation and supination—beyond the flexion-extension response that was the primary design target—suggests that the system has latent multi-degree-of-freedom sensing capability that was not fully exploited in the current single-axis estimation framework. This finding broadens the platform's potential scope beyond elbow flexion estimation toward a more comprehensive upper-limb posture-sensing system, motivating the multi-DOF extension.

5.3 Future Work

5.3.1 Sensor Fusion Implementation and Validation

The most immediate priority for future work is the completion of the proposed sensor fusion pipeline. Once this dataset is assembled, a polynomial regression model can be fit to the labeled capacitive calibration data, the IMU functional calibration can be performed to establish the anatomical flexion axis, and the confidence-weighted fusion estimator can be evaluated against ground truth across both static and dynamic conditions. The primary performance metric of interest is the root-mean-square error (RMSE) of the fused angle estimate relative to the goniometer reference, compared with the capacitive-only and IMU-only baselines to quantify the benefit of fusion.

5.3.2 Multi-Subject Evaluation

All experimental data reported in this thesis were collected from a single subject. A multi-subject evaluation is necessary to assess the system's gener-

alizability across different arm geometries, muscle bulk distributions, and skin-electrode contact properties. Of particular interest is the inter-subject variability of the capacitive baseline count values and per-channel sensitivity slopes, which will determine whether a universal calibration model is feasible or whether per-subject calibration is required for clinical deployment. A multi-subject study should also assess the consistency of the fabrication process across multiple sleeve instances, as electrode placement variability across fabrication runs may introduce sleeve-to-sleeve differences in capacitive response that must be characterized and compensated for.

5.3.3 Multi-Degree-of-Freedom Estimation

The current system targets elbow flexion-extension as a single degree of freedom. The experimental results demonstrate that the four-channel capacitive array is sensitive to forearm pronation and supination through its deformation response, and the dual-IMU configuration captures full three-dimensional relative orientation between limb segments rather than a single joint angle. Extending the estimation framework to jointly estimate elbow flexion angle and forearm rotation angle, the two primary degrees of freedom of the distal upper limb, would substantially increase the clinical utility of the system. This extension would require a denser electrode array to improve spatial resolution for torsional deformation sensing, a two-dimensional regression or machine-learning model to map the multi-channel capacitive feature vector to joint-angle pairs, and a corresponding extension of the IMU fusion to extract both flexion and rotation angles from the relative-quaternion output.

5.3.4 Electrode Durability and Washability

The long-term durability of the copper tape electrode array under repeated mechanical cycling, exposure to perspiration, and laundering has not been evaluated in this thesis. For clinical and athletic rehabilitation applications, a wear-

able garment must withstand repeated donning and doffing, extended wear during physical activity, and routine washing without degradation of electrode integrity or electrical continuity. Future work should characterize the fatigue lifetime of the adhesive bond between the copper tape and the athletic substrate under realistic mechanical loading conditions, evaluate the effect of perspiration and moisture on electrode conductivity and CapTIvate baseline stability, and explore encapsulation strategies, such as conformal polymer coatings or thermally bonded conductive fabric overlays, that can extend electrode durability while preserving the mechanical compliance and comfort of the sleeve.

5.3.5 Miniaturization and Clinical Integration

The current system prototype, while functional, retains the form factor of a research platform. The MSP430 PCB and ESP32 enclosure are discrete modules connected via wire leads, and the overall assembly is larger than desirable for a clinical wearable product. Future hardware iterations should pursue full integration of the capacitive-sensing PCB and ESP32 into a single, compact module, ideally embedded within the sleeve itself or housed in a low-profile, wrist-mounted enclosure that does not impede movement or attract clinical attention. Power management should be addressed through the implementation of a rechargeable battery management circuit, sleep-mode scheduling for the BLE radio during non-transmission intervals, and profiling the overall system current draw to determine practical battery life for clinical session durations. Integration with clinical data management platforms—such as electronic health record systems or rehabilitation outcome-tracking software—would further enhance the system's translational value for physical therapy applications.

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