Biomedical Sensing - A Sensor Fusion Approach for Improved Medical Detection and Monitoring

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***Abstract*—Enhanced technological advancement in computation, communication, and sensing has dramatically changed the dynamics of modern medicine. Advancing preventive medicine is paramount to a sustainable improvement in the quality of life and life expectancy. On-body sensors provide continuous measurements for healthy and ailing individuals leading to faster recovery and more timely detection of illnesses. Novel sensor designs and sensor fusion for preventive monitoring can provide extensible benefits, including a better understanding of ailment progression, treatment optimization, and patient feedback through data analytics and visualization. This article presents the development of an ex-vivo sensor fusion system to track a person's muscular condition. The embedded system provides a significant benefit by notifying users of particular events in real time.**

***Index Terms*—Medical Diagnoses, Tissue Fingerprinting, Biomedical, Communication, Sensing.**

I. Introduction

Medicine has evolved from ancient practices based on herbalism and religious beliefs to a science-based approach that relies on rigorous research and experimentation. Biomedical sensing has played a critical role in this evolution, particularly in data collection and analysis. Wearable biomedical sensors have emerged as a promising solution that can provide real-time health information, detect early signs of health problems, and integrate into daily life without lifestyle changes.

Wearable sensors can capture physical inputs from various sources, including muscular tissue, and convert them into usable information. The advancement and miniaturization of these sensors have made it possible to integrate numerous sensing capabilities into a single instrument, incorporating them into a user's daily life through wearable sensors. Wearable biomedical sensors can be embedded into apparel, watches, jewelry, and more, and can be used for a range of applications, from detecting early signs of muscular dystrophy in athletes to monitoring muscular tissue health in general.

Despite the numerous advantages of wearable biomedical sensors, several challenges persist. For instance, the devices must have access to ample resources, including storage, power sources, and computational accessibility, to continuously read and gather data from the user. Capturing as much raw data from biological sensors enhances the detection, which is a challenge for a device with limited resources. Therefore, devices with higher capabilities, such as smartwatches, are currently the most examined solution. Communication is another challenge that many biomedical sensor designs incur. Therefore, improvements in communication provide numerous benefits [1], [2], including the ability to provide parallel communication via different sensors, monitoring mobile patients, and increase the availability of useful data through raw data transmissions [3]–[5].

Biomedical research and nanotechnology have significantly accelerated the development and usage of wearable sensors. Biomedical sensors contribute to medical diagnosis and treatment by further analyzing one's health and are a critical part of different medical diagnostic equipment, such as the electrocardiogram (ECG), which records electrical signals given off by the heart to check for various types of heart conditions. However, many ECG devices require the use of multiple attachments and wires.

Improvement of biomedical sensing capabilities and devices is vital for several reasons, including more accurate and faster detection, less intrusiveness, and more automation. For example, improving muscular tissue detection capabilities can drastically improve the quality of life for individuals, athletes, and patients suffering from muscular dystrophy. The most common testing methods often require users to carry separate devices, which can be cumbersome and inconvenient. Thus, individuals miss important events that lead to better treatment and preventive management.

This paper will focus on the importance of sensor fusion for biomedical applications, including muscular tissue detection, and propose improvements in sensor development. Section II provides a literature review of wearable biomedical sensors, including muscular tissue detection, and Section III discusses proposed improvements. Section IV presents concept designs, and Section V provides the conclusion and future work.

II. Literature Review

Biomedical sensors have become essential for monitoring an individual's health status in real-time. These sensors aim to continuously detect a patient's physiological, neurological, or chronic behavior during everyday life, providing valuable data for medical diagnosis and treatment. Recent advancements in biomedical sensing have focused on developing new sensing mechanisms, such as wearable and implantable devices, biomaterials, and textile technology [6]–[8].

Printable electronics have also emerged as a promising technology for biomedical sensing due to their low cost, high flexibility, and compatibility with various substrates [9], [10]. Furthermore, frequency has been explored as a sensing mechanism for biomedical applications, including glucose monitoring [11] and wireless communication between implantable devices [12].

Biomedical sensors exist for both in-vivo and ex-vivo applications. In-vivo sensors are designed to be implanted or ingested inside the body, providing continuous monitoring of physiological signals or targeted drug delivery [13], [14]. Ex-vivo sensors, on the other hand, are used externally to monitor various physiological signals, such as heart rate, blood pressure, and oxygen saturation [15].

Recent advancements in biomedical sensing have provided a wide range of possibilities for monitoring an individual's health status. These advancements in sensing mechanisms, sensor fusion, and in-vivo and ex-vivo sensors are crucial for facilitating medical diagnosis and improving healthcare quality.

A. In-Vivo Sensing

Incorporating surgical implantable biomedical sensors is a different approach to diagnosing and treating patients by physically placing sensors inside the patient's body to target the area of interest. In-vivo sensors have been developed for a range of applications, including monitoring glucose levels, blood pressure, and brain activity. For example, brain implants can be used to detect and treat neurological disorders such as Parkinson's disease and epilepsy. The use of in-vivo sensors has opened up new possibilities for medical diagnosis and treatment.

One specific example of an in-vivo sensor is the CardioMEMS Heart Failure (HF) sensor, which is used to monitor patients with heart failure. Patients in NYHA class III are comfortable when resting, but can experience fatigue, shortness of breath, and angina pain when performing normal or less-than-normal physical activities such as walking [16]. The CardioMEMS HF sensor is implanted in the patient and collects hemodynamic data to monitor the patient for signs of heart failure.

However, the use of implantable sensors is not without its drawbacks. Implantation can be an invasive and painful procedure, and the sensors themselves can cause inflammation, infection, and rejection by the body. In addition, implantable sensors may not be able to provide continuous monitoring and may require regular calibration or replacement. Furthermore, implantable sensors often require energy harvesting or storage to function, which can be a limiting factor in the development of the devices.

These limitations have motivated researchers to explore alternative solutions such as ex-vivo sensors, which can be used outside of the body. Ex-vivo sensors can be used for a range of applications, including monitoring biochemical reactions, testing drug efficacy, and diagnosing diseases. These sensors can be designed to be highly sensitive and specific, and can be used in a variety of settings, such as in a laboratory or at the point of care. The development of ex-vivo sensors has the potential to revolutionize medical diagnosis and treatment, as they can be used in a wide range of applications without the risks associated with implantable sensors.

B. Wearable Sensors

Wearable sensors can be both intrusive and unobtrusive. Current devices to measure Electroencephalogram (EEG) signals can be intrusive to a user's freedom due to the number of sensor patches, cables, and data collection devices. Unobtrusive sensors are less invasive, such as smartwatches, jewelry, bands, etc., and environmental sensors that capture data without being attached to the target of interest.

Mahmud et al. developed a wearable ring sensor to continuously and remotely monitor the user with minimal invasiveness, or overhead [17]. Sanfilippo et al. developed a sensor that monitors the heart using an ECG sensor, providing the wearer with vibration feedback and a push-button allowing the patient to report an emergency or accident [18].

Smartwatches are very popular for biomedical sensing due to their flexibility in integrating multiple devices and power availability. Smartwatches often have multi-sensor capabilities, including integrated optical photocells, electrical pads, accelerometers, compasses, gyroscopes, GPS, barometer, ambient, pulse oxygen sensors, photoplethysmographic (PPG), and many more. Many of the built-in sensors allow for biomedical data collection and monitoring.

Alternatively, other methods showing promise embed biomedical sensors in textile material, woven into clothing for various detections, including respiratory information [19]. A synergy between the different sensing designs can offer many benefits. However, the difficulty of connecting, incorporating, and developing new sensors to provide accurate data collection and interpretation with minimal disturbances remains challenging.

Unlike other applications, biomedical sensors misrepresenting data can lead to irreversible damage, with false negatives being the worst case. If a problem exists and goes undetected, the patient may assume everything is normal and not seek medical assistance in time for proper treatment. Thus, misdetection is one of the primary reasons that off-the-shelf devices do not provide clinical diagnoses. Instead, the current devices only deliver a suggestion.

It is critical to advance research in biomedical sensors to overcome the current limitations. Improving the current state of biomedical sensing is vital to offer better and more efficient health monitoring and provide enhanced accessibility and availability. Moreover, improvements in various areas are necessary, including integration to allow for data sharing between patients and medical professionals [20].

C. Textile Technology & Tactile Sensing

Textile technology is increasingly being used to implant biomedical sensing, using various technologies such as printable electronics and stretchable, conductive materials. Integrating sensors into fabrics makes it possible to create clothing, furniture, and other items that can capture a range of environmental and biometric data.

One approach to implanting sensors into textiles involves embedding piezoresistive materials such as polyvinylidene fluoride film (PVDF) or electromechanical film (EMF) into clothing [19]. For example, Choudry et al. have embedded piezoresistive sensors into fabrics to measure changes in electrical resistance resulting from mechanical stress [21]. Other researchers have used sensor arrays composed of PVDF films to detect pressure and cardiovascular signals and extract heart and respiration rates when attached to a patient [22], [23].

Textile technology also provides a valuable means of tactile sensing, allowing for measuring information from physical interactions with the environment. This technology has applications for both users and robotics. By providing tactile feedback, users can better interact with virtual environments, and robotics can feel and respond to interactions with their environment. It also has the potential to revolutionize virtual environments by providing haptic feedback that more closely replicates physical interactions. Overall, textile technology offers a promising avenue for developing unobtrusive sensors for capturing and analyzing patient behavior data.

D. Microwave Frequency Sensing

Many biomedical sensors use frequencies for monitoring and early detection of certain anomalies within the patient. The radio frequencies in biosensors rely on producing electromagnetic fields to engage with matter depending on its molecular structure [24]. Electromagnetic waves penetrate the material, tissue, or muscles to achieve noninvasive measurements. The microwaves are non-ionizing fields, refraining from harmful types of radiation, similar to X-rays and gamma rays. Hence, many researchers aim to use radio frequencies, including microwave biosensors, to detect malignant or benign tumors within the body due to the tissue's high dielectric properties [25] [26]. RF sensing can detect tumors but differentiating between cancer and benign remains challenging due to the similar water content. Similarly, Costanzo et al. described glucose measurements through frequency shifts [24]. In many cases, sensors equip transducers that convert received signals into measurable electrical signals to convert the raw data into a format understandable to the users.

Ultra-wideband signals (UWB) offer a safer approach, lower cost, and can permeate through skin, bones, and tissues. UWB signals are used more frequently due to their low power transmission levels for safer radar-based applications and noninvasive measurements based on electromagnetic fields [27]. For example, UWB signals can detect breast cancer using low-risk imaging.

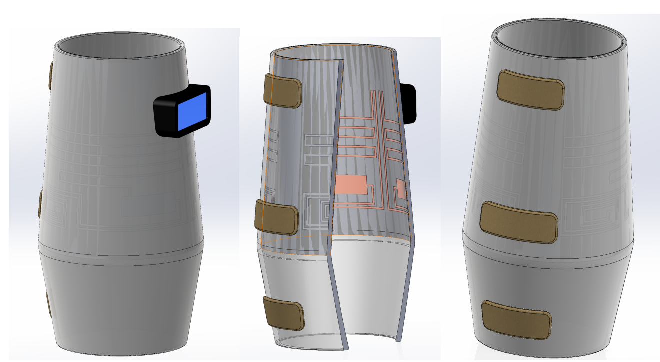
Song et al. use UWB signals to detect tumors and extract the response by the reflected signals, which then scatter [28]. A dielectric discontinuity reflects an interrupting wave. The radar estimates the existence and location of the interruption, and artifact removal algorithms are sometimes necessary to remove noise and align original and reference experiments.

IEEE 802.15 Task Group 6 is developing a UWB signal communication for body area network (BAN) applications. It will use small, low-cost, low-power wireless devices implantable in the body or on the body intended to provide high penetration capability, high precision, and short-range wireless communication to or inside the human body [29]. Therefore, radio frequency can offer early detection of unknown anomalies, imaging, and remote monitoring of vital signs, such as heart rate and blood pressure.

E. Sensing Methods

The use of biomedical sensors for continuous health monitoring has revolutionized healthcare. Various sensing methods are available that can measure physiological signals related to human health and well-being. In addition to EEG, ECG, and PPG sensors, optical sensing techniques, such as pulse oximetry and functional near-infrared spectroscopy (fNIRS), are gaining popularity in wearable biomedical sensors. Pulse oximetry measures the oxygen saturation level of arterial blood and can be used to detect respiratory disorders such as sleep apnea, chronic obstructive pulmonary disease (COPD), and asthma. fNIRS measures the hemodynamic response in the brain and can be used to detect neural activity related to cognition, language processing, and emotion.

Wearable sensors have also been developed for other physiological signals, such as skin conductance, which reflects emotional arousal, and electromyography (EMG), which measures



(a) (b) (c)

Fig. 1: Prototype Design

muscle activity [30]. Skin conductance sensors have been used to detect stress, anxiety, and depression, while EMG sensors can be used for muscle function assessment and rehabilitation. Additionally, sensors that measure blood glucose levels, lactate concentration, and interstitial fluid pressure have been developed for diabetes management and sports performance optimization [8].

The development of newer sensing methods and materials has expanded the range of wearable biomedical sensors. For example, flexible and stretchable sensors have been developed for conformal integration onto the skin, enabling comfortable and long-term wearable sensing [31]. In addition, sensors that use nanotechnology, such as nanowires and nanotubes, have shown high sensitivity and specificity for biomolecular detection [6]. These advancements in sensing technologies have led to the development of new types of biomedical sensors and wearable devices that can be used for a range of applications, such as disease detection, health monitoring, and sports performance optimization.

The ability to use these sensors for disease detection and monitoring is widespread in research. Wearable sensors that incorporate these sensing methods have been used to quantify anxiety for sports performance [32] and detect an individual's cardiac status, such as breathing signal, heart apex pulse, and mechanical heart behavior for cardiac monitoring [33]. Nerve activity may prompt changes in heart rate, blood pressure, and respiration during a stressful period. Moreover, these sensors are good indicators of brain activity, hormonal secretion, and more, providing valuable insights into human health and well-being. The advancements in sensing technologies and materials have led to the development of newer sensing methods, such as skin temperature, sweat analysis, and bioimpedance, expanding the range of wearable biomedical sensors [9], [34], [35].

F. Sensor Fusion

Sensor fusion is essential in many applications, including healthcare, enabling more accurate and reliable sensing capabilities. The integration of different sensors can provide complementary information and improve overall performance. Advanced sensor fusion techniques can promote more accurate predictions and a better understanding of the environment or user behavior [36].

There are two primary categories of sensor fusion: active and passive. Active sensor fusion requires collaboration between sensors to achieve a common goal, such as synchronizing data captures to provide more accurate information [36]. In contrast, passive sensor fusion utilizes data captured from different sensors independently and combines them as supplemental information. Effect-based sensor fusion is an example of passive sensor fusion, where captured data correlates with the system's condition and environment.

Multi-sensor fusion is another popular approach that involves collecting signals and data from multiple sensors to reduce uncertainty and improve overall performance. This technique is widely used in different applications, such as robotics and autonomous systems, to enable a better understanding of the environment and perform more accurate tasks. For instance, multi-sensor fusion can help robots navigate unknown environments by integrating data from different sensors [37].

Sensor fusion is critical in enhancing sensing capability and accuracy in various applications. Active and passive sensor fusion techniques and multi-sensor fusion provide different approaches to integrate sensor data and improve overall performance. Future research in sensor fusion will focus on developing advanced techniques that enable more accurate predictions and a better understanding of the environment or user behavior.

III. Proposed Improvement

The study presented a novel approach to biomedical sensing through the development of a prototype that enables direct area detection on various parts of the body. To achieve this, the research team used a range of materials such as stretchable fabric, ninjaflex, and various 3D printed materials, including rigidity designs for testing purposes. The prototype integrated sensors and an embedded computer that could capture signals and determine various ambient information, making it possible to differentiate between muscular conditions. Although the current design only detects muscular contraction, future work will focus on improving the design to test for differences between various tissues. In addition, the study collected data on communication to correlate data between the sensors, including the delay.

As shown in Figure 1, the prototype utilized a stretchable material to attach to sensitive muscle areas and embedded RF signal generation to provide a repeatable three-dimensional scan of various fingerprint conditions. The prototype offered a distributed implementation with a wireless connection for transmitting collected data, with raw data captures sent for

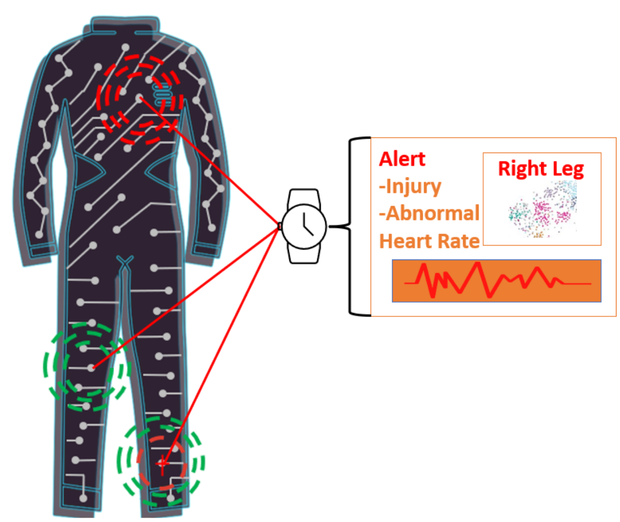


Fig. 2: Distributed Sensing & Sensor Fusion

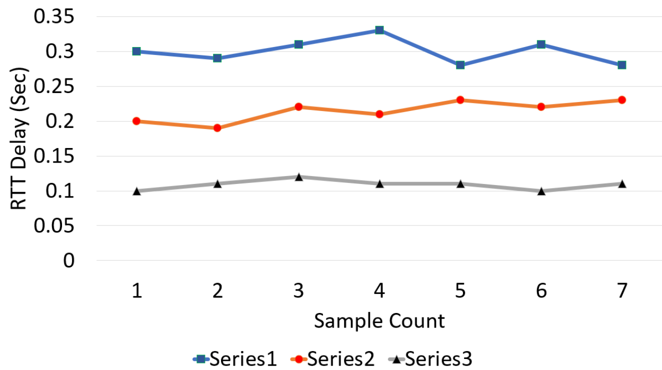


Fig. 3: Communication Delay

learning model and fingerprinting. Future designs will focus on providing edge computing and data preprocessing to rely on distributed processing. This approach holds great promise for improving healthcare and enhancing the quality of life for individuals, with the potential to detect and treat ailments that were previously undetectable.

Figure 2 provides a glimpse into the potential applications of the developed sensors. The distributed functioning of the sensors ensures independent operation, with collected data transmitted to a central processing unit for analysis. The central unit plays a crucial role in the system, with responsibilities such as receiving data, updating the sensor algorithms, and maintaining the status of each sensor. However, each sensor can process data and deduce the general condition, ensuring the ability to detect ailments at a specific location. The use of soft material for direct sensor attachment and user comfort is an essential feature of the prototype. However, future design plans will include improvements such as power harvesting, electronic miniaturization, and communication antenna designs to ensure minimal overhead and user interference.

The summer research team's integration of this novel approach to biomedical sensing offers exciting possibilities for direct area detection and real-time monitoring of various physiological signals. By using a combination of materials and sensors, this prototype provides an innovative and promising solution for detecting and treating ailments. Moreover, the approach holds the potential for integration into mainstream medical devices, providing new opportunities for novel discoveries in disease detection and treatment, leading to improved healthcare and enhanced quality of life for individuals.

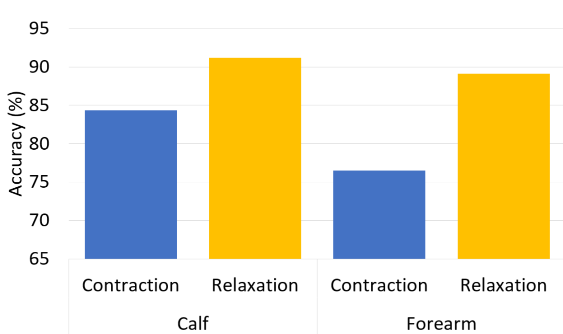


Fig. 4: Muscle Contraction & Relaxation Detection Accuracy

IV. Results

The experimental testbed employs several Raspberry Pi PicoW units, a low-cost development board that provides superior communication capabilities. The Pico-W can be used as a soft access point, allowing cluster communication and energy conservation. Figure 3 presents the communication delay between the various IoT devices. To ensure correct time synchronization, the experiment records round trip times (RTT) instead of end-to-end delays. End-to-end delay measurements can be problematic due to the possible drift and invalid timestamps. The RTT results depict the time taken for sequential sensor data collection, with an average sampling time of around 108 ms per distributed unit.

Finally, Figure 4 illustrates the accuracy of muscle contraction in different body areas, such as the forearm and calf. The results show the average over several captures, with the forearm and calf muscles combined. The accuracy is determined using thresholding, and the calf muscle provided more discernible detection. These results indicate the prototype's effectiveness in detecting muscular contractions, and future designs will aim to improve detection accuracy while expanding the sensors' capabilities to test differences between various tissues. This approach holds great promise for detecting and treating ailments that were previously undetectable, leading to improved healthcare and enhanced quality of life for individuals.

V. Conclusion

The advancements in biomedical sensing have revolutionized the field of medicine, with significant improvements in the quality of life and overall well-being of individuals. The ability to capture conditional medical data from individuals can lead to better preventive medicine, treatments, and the discovery of new cures. While devices with higher capabilities, such as smartwatches, rings, or non-wearable devices, implement many biomedical sensors, it is still essential to develop biomedical-specific sensors for acquiring more targeted data. This paper sheds light on various challenges associated with biomedical sensing and its applications.

The development of testing equipment to capture tissue-specific data during normal day-to-day activities and ailments is critical for future work. By tracking the progression of medical conditions and improvements, researchers can investigate why some individuals recover faster than others and determine the parameters for the developmental periods. This approach will help better understand the physiology of the body and how it reacts to different conditions.

Moreover, the successful integration of biomedical sensing with data analytics and visualization can provide a more comprehensive understanding of an individual's health condition. It is possible to achieve preventive monitoring and treatment optimization using the data collected from biomedical sensors. However, the adoption of biomedical sensing in the mainstream medical community faces various challenges, including the need for extensive research, ethical concerns, and regulatory requirements. Therefore, there is a need to overcome these challenges to realize the full potential of biomedical sensing and its applications.

In conclusion, biomedical sensing has the potential to revolutionize the healthcare industry by providing more targeted and personalized healthcare solutions. Developing specialized sensors and testing equipment, coupled with data analytics and visualization, can significantly improve the quality of life for individuals. Nonetheless, further research, ethical considerations, and regulatory requirements need addressing to ensure the safe and effective integration of biomedical sensing in the mainstream medical community.

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