Design of a Reconfigurable Multimodal Wearable Sensor Network (RMWSN) for Human Health and Ambience Monitoring

Surendar Devasundaram[1], Andrea Raymond[2], Mark Aldritz Dela Virgen[2], Drue Shapiro[2] and Joon-Hyuk Park[2,a]

[1]*Department of Electrical and Computer Engineering, University of Central Florida, Orlando, Florida, U.S.A.*
[2]*Department of Mechanical and Aerospace Engineering, University of Central Florida, Orlando, Florida, U.S.A.*

Keywords: Reconfigurable, Multimodal, Wearable Sensor Network.

Abstract: The studies of human physiology, movement biomechanics and environmental interaction are generally conducted in laboratory settings using standard lab equipment such as Electrocardiography (ECG), respiration belt, motion capture cameras and a force-plate instrumented treadmill. With recent advancements in wearable technology, research on human behaviour, physiology and biomechanics in real-world environments has become much more viable and offers a means to collect real-world data from a broader range of activities. However, current wearable devices are typically a stand-alone system, each employing its own hardware and software interfaces that often vary between different systems, thus making it difficult to simultaneously integrate and instrument them on a user for synchronous multimodal measurements. To overcome this limitation, we propose a reconfigurable multimodal wearable sensor network (RMWSN) for real-time monitoring and data acquisition of various biomechanics, physiological and environmental parameters. The RMWSN incorporates a two-tier sensor network: the first tier utilizes wearable sensors with a microcontroller and the second tier consists of an efficient edge computing device for real-time data processing, data logging and wireless data transmission. The novel feature of the system that differentiates itself from existing wearable sensor systems is the modular and reconfigurable design in a wearable form, its scalability, easy accessibility, and integration with external computing devices. The outcomes of this research demonstrate an efficient multimodal wearable sensor network for use in many applications for human health and ambience monitoring.

1 INTRODUCTION

Wearable devices consist of electronics and computers integrated into apparels or other materials to be worn comfortably on the body. Applications of wearable technology in health care are broad: vital signs monitoring, disease detection, joint angles measurement, concussion monitoring, gait biomechanics (Adesida et al., 2019; Wu & Luo, 2019). Military application is another area where wearable devices are used to monitor soldier's behaviour, stress level, emotions, fatigue, and the environment to help improve awareness of the soldier's state (Seshadri et al., 2016). Ambience parameter measurement such as air temperature, humidity, pressure, sound, light intensity using wearable devices have been also used for enhancing the safety and health of the employee in the workplace (Maltseva, 2020). Similarly, Wearable Environmental Monitoring System (WEMS) measures atmospheric parameters like temperature, pressure, humidity, and air pollutants (Al Mamun & Yuce, 2019). Further, wearable devices are utilized for education purposes as well, e.g., monitoring autistic children for the safety in school settings and informs the caregivers and teachers about the child's physical and mental status (Sandall, 2016).

The short-term impact of the environment on the human body was examined by fusing physiological data and environmental data collected in real-world settings, for example, a recent study found that environmental and physiologic parameters are correlated, specifically, noise, UV and air pressure have effects on heart rate, electrodermal activity, body temperature and motion (Kanjo et al., 2018). This work demonstrates that multimodal sensor data

[a] https://orcid.org/0000-0001-9038-4981

Devasundaram, S., Raymond, A., Virgen, M., Shapiro, D. and Park, J.
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DOI: 10.5220/0010838100003118
In *Proceedings of the 11th International Conference on Sensor Networks (SENSORNETS 2022)*, pages 26-33
ISBN: 978-989-758-551-7; ISSN: 2184-4380

can infer more comprehensive and multi-domain data that would help understand the individual's state and make more accurate detection and prediction. Traditionally, the motion data from IMU is used in human activity detection but with the use of physiological and ambient data from multimodal measurement can enhance the accuracy of prediction as the uncertainties associated with inertial sensors are eliminated (Nweke et al., 2019). The data-level, feature-level, decision-level, multi-level algorithms for multi-sensor fusion in body sensor network (BSN) was introduced (Fortino et al., 2019). These previous works have pointed out that a holistic multimodal wearable sensor network is essential to achieve high fidelity and accurate information of a person.

Commercially available wearable devices are designed to provide specific measurement capabilities, generally not exceeding a few sensing modalities. Most wearable devices come with proprietary hardware and software module that are designed as stand-alone devices. Some products do offer a means to relay the data to other external devices or have a separate channel for trigger or sync signals. Nevertheless, the main challenge is when integrating different sensor systems into a single unified system for simultaneous and synchronous multimodal measurement, due to the variation in mechanical, thermal, and electrical configurations and characteristics of each system. Moreover, different communication protocols between make it more difficult to implement multi-sensor fusion algorithms (Lou et al., 2020). Wearable devices, in general, do not take into consideration the necessity of customizable sensor configuration, lacking the ability to be reconfigured to function in different applications (Walker et al., 2016). This calls the need for a more modular and reconfigurable sensor network with intuitive software architecture.

A reconfigurable multimodal wearable sensor network (RMWSN) is presented in this work for real-time monitoring and data acquisition of various biomechanics, physiologic and ambient parameters. The central idea is that modularizing a wearable sensor system into sub-systems and identifying a suitable multi-tier sensor network topology such that reconfigurability of the sensor network is achieved without affecting the functionality and integrity of individual sensor nodes. Direct benefits of developing a reconfigurable multimodal wearable sensor network include ease of system integration, adaptability to different applications and most importantly, enabling holistic data acquisition of multimodal parameters.

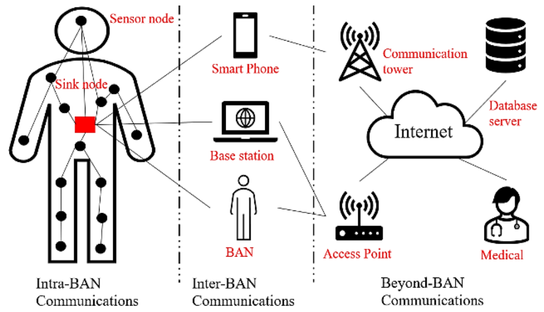

Figure 1: Architecture of WBAN.

Wireless Body Area Network (WBAN) was first introduced in (Van Dam et al., 2001). WBAN is a branch of Wireless Sensor Network (WSN) but the characteristics differ slightly to suit the application that uses body-worn, around the body and in-body sensors (Latré et al., 2011; Yong-Min et al., 2009). The communication of data in WBAN is a 3-tier process as recognized in IEEE 802.15.6 standard for WBAN (Figure 1). In tier-1 (also known as Intra-BAN communication), communication among sensor nodes and between the base station and sensor nodes occurs. In tier-2 (also known as Inter-BAN communication), communication between the Access Points (APs) and the base station, communication between two different BANs occurs. In tier-3 (also known as Beyond BAN communication), as the name suggests, the communication occurs beyond the BAN. This tier also involves communication between different access points and medical servers through the internet. In the standard WBAN architecture, a sink node collects the sensor data from different sensor nodes distributed across the body and sends it to the base station and the base station forwards the sensor data to the access points which then is relayed to the remote systems through a gateway via internet.

2 SYSTEM ARCHITECTURE

RMWSN employs a different network configuration as compared to WBAN. In this network (Figure 2), reconfigurable and modular sensor node collects multimodal data such as physiological, biomechanics and ambience parameters, and use a powerful single board computer as the enhanced base station. The multimodal data from each sensor node distributed across the body are collected by the enhanced base station and it acts as an access point to relay the data to the remote systems via internet. This eliminates the need for separate access point hardware. It also serves as an edge computing device to perform real-time analysis on the collected data and transmit the

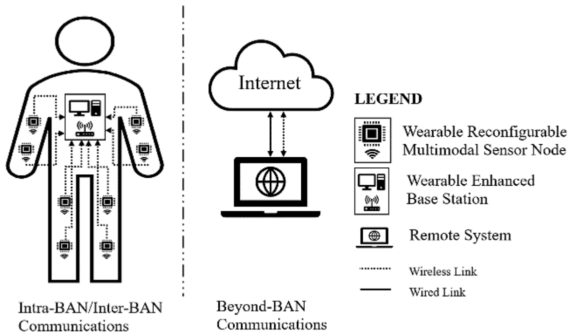

Figure 2: Proposed Reconfigurable Multimodal Wearable Sensor Network (RMWSN).

inference to the remote systems. This network doesn't require the sensor nodes to communicate amongst each other; hence, a star topology with single-hop communication is appropriate where reconfigurable multimodal sensor nodes communicate directly with the enhanced base station. The key characteristics of the RMWSN are:

1. Enhancing a single sensor node to collect multimodal data by incorporating modular and reconfigurable design techniques.
2. Combining the functionality of sink node and the base station into a single hardware and refer it to as the enhanced base station.
3. Enabling the inter-BAN and beyond-BAN communication from the enhanced base station.
4. Implementation of real-time data processing and data analysis on the enhanced based station.

The RMWSN offers more versatile, reconfigurable, and modular configuration of the sensor nodes to expand the adaptability of the system for use in different applications, and multimodal sensor network offers enhanced functionality of the base station to perform real-time analysis of multimodal data. Compared to the traditional sensor networks, such as WBAN which require multiple communication channels to collect multimodal data, RMWSN's sensor node uses a single communication channel and reduces the network complexity.

3 MODULAR AND RECONFIGURABLE SENSOR NETWORK

3.1 Sensor Unit

MEMS sensors are used to develop reconfigurable multimodal sensor node with a small form factor and several external interfaces are designed for the MEMS sensors (Figure 3).

Different communication interfaces and power supply were necessary to be compatible across different MEMS sensors: common operating voltage required ranges between 1.8V and 3.3V and the common digital communication protocols are Inter-Integrated Circuit (I^2C), Serial Peripheral Interface (SPI) and Universal Asynchronous Receiver/Transmitter (UART).

The design criteria of the individual sensor unit are the following (Figure 4): 1) MEMS Sensor with small form factor, 2) facilitate digital communication, 3) operating voltage between 1.8V and 3.3V, 4) overall size does not exceed 15 mm by 15 mm, 5) PCB size should not exceed 13 mm by 13 mm and the thickness of should not exceed 1.6 mm, 6) Top layer should contain the sensor module and optionally, voltage regulator if the operating voltage is less than

Table 1: Summary of Sensor units.

Category	Sensor	Components	Interface	Operating voltage	Range	Resolution
Physiological	PPG	SFH7050+AFE4404	I^2C	1.8-3.6V	0-4V	24 bit
	Temperature	MAX30205	I^2C	2.7-3.3V	0-50°C	16 bit
	EDA/GSR	Ag-AgCl electrode + LM324 + ADS1115	I^2C	2-5.5V		16-bit
Motion	Accelerometer	ICM20948	I^2C	1.7-1.95V	±2 -±16g	
	Gyroscope				±250-1000dps	
	Magnetometer				±4900µT	
Ambience	Temperature	TMP117MAIYBGR	I^2C	1.8-5.5V	-55-50°C	16-bit
	Pressure	MPL3115A2	I^2C	1.6-3.6V	20-10kPa	20-bit
	Humidity	SHTC3	I^2C	1.6-3.6V	0-100 %RH	0.01 %RH
	Ambient Light	VEML6030	I^2C	2.5-3.6V	0-120 klx	16-bit
	Air Quality	CCS811B-JOPD500	I^2C	1.8-3.6V	eCO_2: 400-8192ppm TVOC: 0-1187ppb	16-bit

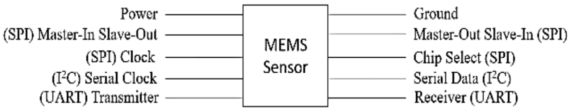

Figure 3: Final abstraction of MEMS sensor external interface.

3.3V, 7) Bottom layer should contain the abstract connector (any connector with 10 position), 8) The center of the connector should be aligned to the center of the board.

To avoid redundancy while adding more modality to the data collected by the sensor node, sensors from different categories such as physiological, biomechanics and ambience were selected for the sensing unit (Figure 5). Photoplethysmography (PPG) sensor which is a combination of light source and photodetector is used to measure important vital signs like heart rate (HR), respiration rate (RR) and blood oxygen saturation (SpO_2). To process the signal and facilitate digital communication, AFE4404 was used. Among many temperature sensing elements like

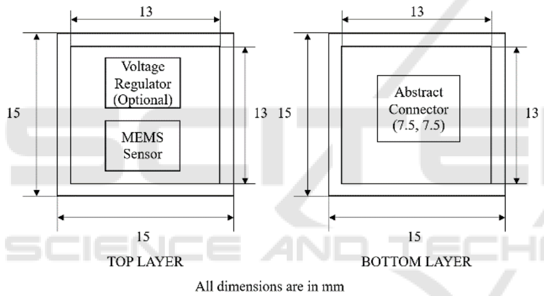

Figure 4: Design criteria for individual sensor unit.

thermocouple, semiconductor-based elements, we have chosen semiconductor-based temperature sensor MAX30205 (3mm x 3mm TDFN package) as human body temperature sensor for many reasons such as limited operating range, very linear with better accuracy, rugged, good longevity and inexpensive. The operating range of this device is 0°C to +50°C.

Inertial Measurement Unit (IMU) consists of 3 types of triaxial sensors: accelerometer, gyroscope, and magnetometer. Accelerometer outputs linear acceleration on three axes in space. Gyroscope outputs angular velocity on three axes in space. Magnetometer outputs the magnetic field strength on three axes with respect ot the Earth's axes. ICM20948 a 9-axis device with 2.5 mW power consumption was selected.

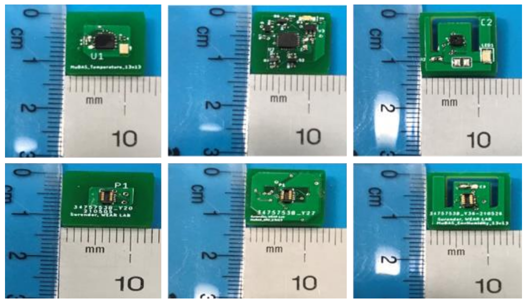

Figure 5: Top layer of sensing unit: (Left) Body Temperature (Middle) IMU (Right) Humidity (Top) Bottom layer of sensing unit: (Left) Body Temperature (Middle) IMU (Right) Humidity (Bottom).

Sensors (Table 1) that measure environmental parameters such as illumination, temperature, noise, vibration, atmospheric pressure, humidity, and air quality are referred to as ambient sensors. Environmental parameters affect a person in three ways: health, performance, and comfort. TMP117 operating between -55°C and 150°C was selected as ambient temperature sensor. MPL3115A2 operating between 20 kPa and 110 kPa was chosen as ambient pressure sensor. SHTC3 was chosen as ambient humidity sensor. VEML6030 was chosen as ambient light sensor. CCS811 was chosen as air quality sensor which measures different types of volatile organic compounds and amount of CO_2.

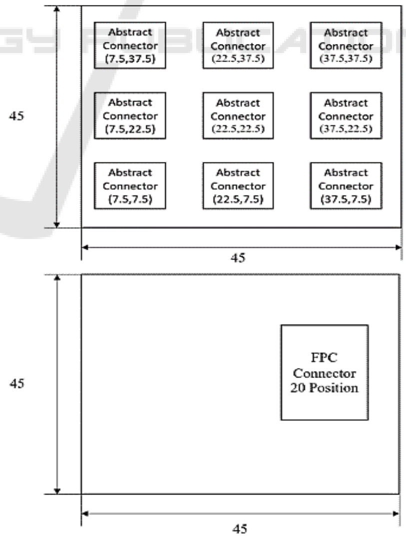

Figure 6: Design criteria for Multimodal Sensor Support Interface (MSSI): (Top) Top Layer (Bottom) Bottom Layer (all dimensions are in mm).

3.2 Multimodal Sensor Support Interface (MSSI)

To design a multimodal sensor node (Figure 6), the processing unit of the sensor node should have the capability to interface multiple sensors. A reconfigurable interface, Multimodal Sensor Support Interface (MSSI), was designed as an interface between multiple sensors and the processing unit of the sensor node. Single row 30 position Flexible Printed Circuit (FPC) connectors and FPC jumper cables are used as an external interface between MSSI and the processing unit, and two row 10 position board-to-board connectors are used as an external interface that mates with the external interface of MEMS sensors (Figure 7).

The design criteria for the MSSI are the following: 1) PCB size should not exceed 45 mm by 45 mm, and the thickness should not exceed 1.6 mm, 2) signal routing should be restricted to top and bottom layer and should not be routed in Ground or Power plane, 3) PCB should be a 4-layer board with the following configuration:

a. Top layer – Abstract Connectors x 9
b. Inner layer 1 – Ground plane
c. Inner layer 2 – Power plane
d. Bottom layer – 20 Position Flexible Printed Circuit (FPC) connector

3.3 Wearable Sensor Node

Wearable sensor node in the RMWSN is responsible for collecting different modality data. Sensing unit, processing unit, communication unit, storage unit and power supply unit are different sub-modules with specific functionality.

Processing unit in the sensor node is responsible for collecting data from the sensor unit (Figure 8). It consists of 32-bit ARM Cortex-M3 microcontroller ATSAM3X8E-AU (84 MHz) and operates between 1.62V to 3.6V. Power supply unit is responsible for managing the power requirements (LP3872) of the sensor node, efficient charging (MCP73831) of the battery and keeps track (MAX1704) of how long the sensor node can operate normally without impacting the accuracy of measurements due to energy exhaustion.

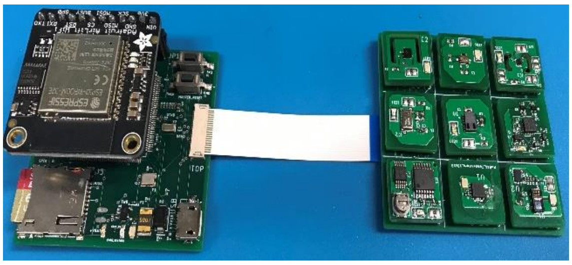

Figure 7: Multimodal Sensor Support Interface (MSSI) housing nine sensor units.

Communication unit is responsible for connecting the sensor node to the base station using wireless communication protocol. Adafruit Airlift Wi-Fi co-processor which utilizes ESP32-WROOM-32 processor (40MHz) was chosen as it provides high flexibility in carrying out the wireless communication. This component can support Bluetooth, Bluetooth Low Energy and Wi-Fi protocols. For our implementation, we have selected Wi-Fi protocol due to higher data rate compared to

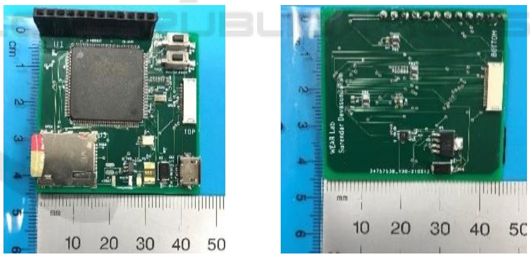

Figure 8: Processing Unit: top (left) and bottom (right) layer.

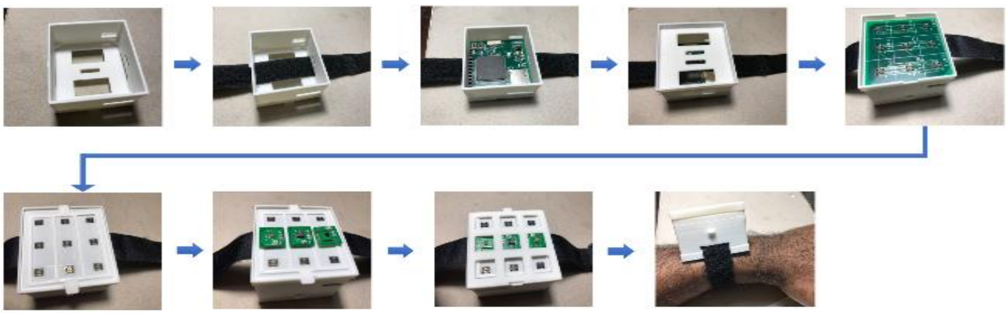

Figure 9: (Left to Right) a) Processing unit enclosure b) Strap through enclosure c) Processing unit PCB placed d) MSSI support enclosure e) MSSI PCB placed f) Sensor removal tray placed g) Sensor unit placed h) Sensor unit covered i) Mounted on body part.

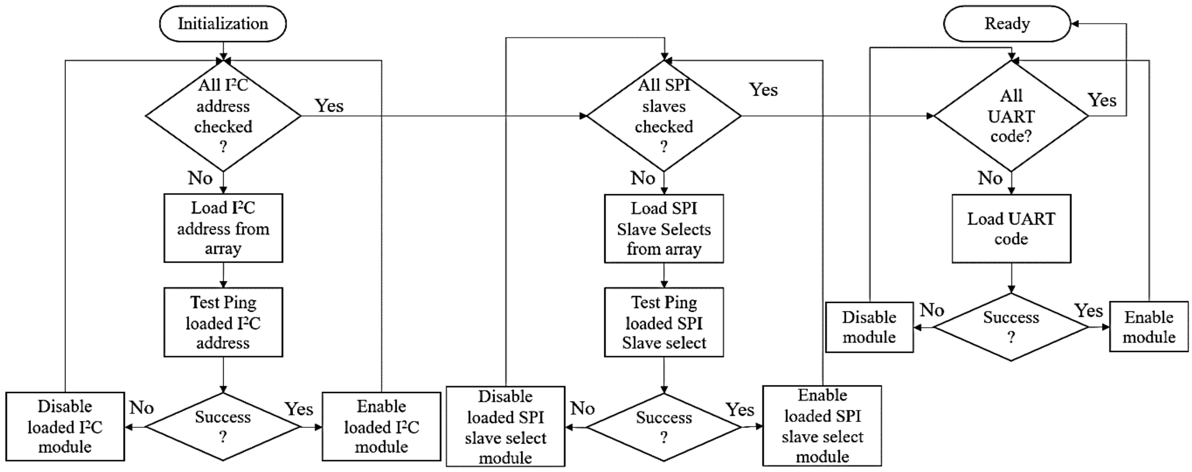

Figure 10: Software flowchart for auto detection and communication configuration of any mounted sensor units.

the other available protocols and it has its own processor to handle the communication thereby reducing the load on the processing unit.

3.4 Base Station

A generic base station is responsible for relaying data from the sensor nodes to the remote systems via internet. To enhance the functionality of the base station to implement on-board real-time analysis, a single board computer (SBC) was selected based on the following criteria: 1) high computation power (Ability to run ML algorithms on-board), 2) can be configured as an access point without additional hardware, 3) on-board wireless module support, 4) small form factor. Among the available commercially of the shelf (COTS) SBCs, Nvidia's Jetson Xavier NX satisfied the above criteria and thus used as the base station for the RMWSN.

3.5 Enclosure

The enclosure for the wearable sensor node should hold 3 types of PCB modules (Processing unit and 2 x Multimodal Sensor Support Interface and 18 x Sensor unit) firmly and it should be comfortable and wearable. The enclosure is designed to fit the processing unit (Figure 9). MSSI PCB fits firmly on the enclosure when the connector is placed on the slot and closes the exposed parts of MSSI PCB except the connectors. The tray support is placed on top of the MSSI. Then, the sensor units are placed on top of the tray support. Finally, the sensor unit is covered on the top using the enclosure similar to the one used to close MSSI with ease. In this final design of the prototype RMWSN, ten sensor units encompassing physiological, biomechanics and ambience sensors are interfaced with MSSI. There are 2 MSSIs, each can support up to 9 sensor units, which serves as a bridge between the multiple sensor units and the processing unit of the sensor node.

4 SOFTWARE IMPLEMENTATION

4.1 Auto Detection and Configuration of the Sensor Units

In order to accommodate any type of a sensor unit mounted on a slot of the MSSI, the processing unit should be able to identify the sensors and the respective communication protocol without manual input from the user. We incorporated an algorithm to auto detect the sensor units mounted on MSSIs and identify the primary communication protocol to be used with each unit (Figure 10). To check the connectivity between different I^2C based sensor units, the address of a single sensor unit is selected from the list created previously and a test communication is performed. If the test communication is successful, the software function or module which is responsible for collecting that specific sensor data and performing basic processing are enabled. If the communication is not successful, then any software function or module related to that sensor unit corresponding to the address is disabled. This process is done till all the I^2C sensor units are checked for connectivity. After checking all the I^2C based sensor units, SPI based sensor units are checked for connectivity between the processing unit and them. For SPI sensor units, identify and develop the list of slave select interface available on the processing unit. Then, select each

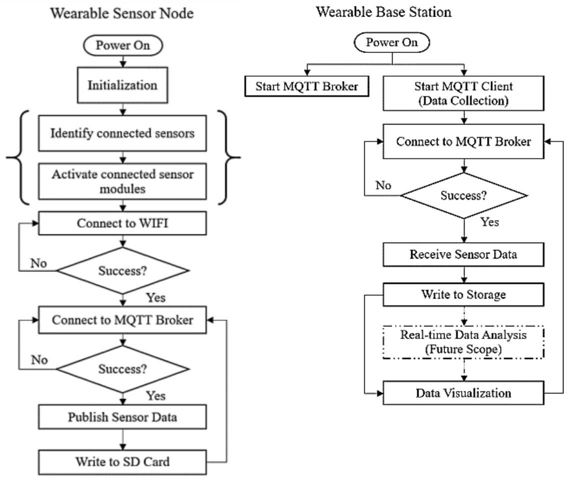

Figure 11: Software algorithm implemented on (left) wearable reconfigurable sensor node, and (right) base station.

slave select interface and perform a test communication a single SPI sensor unit from the list. Since slave select interface is unique for each slot in MSSI, a test communication for all SPI sensor units is done for single slot on the MSSI. If the communication is successful, the software function or module responsible for collecting sensor data and performing basic processing are enabled otherwise those are disabled. This process is done for all the 17 other slots in the MSSI to identify all the SPI based sensor units in MSSI. Finally, connectivity of UART based sensor units are checked. Based on the list of compatible UART sensor units, test communication for each device is done. If the communication is successful, the software function or module responsible for collecting sensor data and performing basic processing are enabled and all the other modules of remaining UART sensor units are disabled as UART protocol can support only one sensor unit interfaced to the processing unit.

4.2 Communication between Sensor Nodes and a Base Station

According to (Kraijak & Tuwanut, 2015), among many protocols, frequently used protocols for Machine-to-Machine communication are Message Queue Telemetry Transport (MQTT), Constraint Application Protocol (CoAP) and Extensible Messaging and Presence Protocol (XMPP). Among these three, MQTT protocol is widely used in IOT due to its lightweight and bandwidth efficiency (Soni & Makwana, 2017).

Reconfigurable multimodal sensor nodes and enhanced base station operate independently but interact with each other over wireless (Wi-Fi) communication using MQTT protocol. On the sensor node side (Figure 11), when the device is powered on, initialization of the central processing unit (CPU) clock, memory, peripherals are done. Then, the node identifies the sensors connected to it. Based on the sensor identification in the previous step, software functions or modules responsible for sensor data collection and basic processing of the sensor data are enabled for use during runtime. Then the node attempts to connect to Wi-Fi till it succeeds. On successful connection, the node proceeds to attempt connection to the MQTT broker running on the base station till it succeeds. On successful connection, sensor node publishes its multimodal sensor data to the base station continuously.

On the wearable base station side (Figure 11), the single board computer is configured as an access point. The base station can act as a MQTT broker (Mosquitto Broker) as well as a MQTT client simultaneously which enables data processing and analysis in real time from the base station as a MQTT client. When the base station is powered on, it starts the MQTT broker. Then, it runs the MQTT client on the base station which is responsible for receiving the published sensor data from the MQTT broker. The client attempts to connect to the MQTT broker until it succeeds. On successful connection, the MQTT client collects the published sensor data from the MQTT broker and writes it to a .csv file in onboard storage. Then, it takes the data stored in the .csv file and does the visualization of the multimodal sensor data.

5 CONCLUSION

The application of wearable technology in a variety of fields makes it ubiquitous. Commercially available wearable systems offer few modality measurement choices and pose challenges in integrating with other systems due to its proprietary software and hardware configuration, making it difficult to reconfigure the sensor system based on the user’s needs for holistic, multimodal measurement. Existing systems act as data acquisition systems and do not perform on-board real-time analysis using machine learning or statistical data analysis algorithms. To address these challenges, a reconfigurable multimodal wearable sensor network (RMWSN) for holistic human and ambient monitoring was proposed and developed.

A modular and reconfigurable design was applied in the development of hardware, consisting of a reconfigurable multimodal sensor node and an enhanced base station. Reconfigurable multimodal sensor node with a power supply unit capable of delivering 4.07 Wh, processing unit capable of interfacing 18 multimodal sensors and a communication unit capable of connecting to the base station using wireless communication protocol were illustrated in this work with a small form factor of 47mm x 47mm x 20mm. A single-board computer was used as a base station, and was configured as an access point, eliminating the need for additional hardware. The base station also can relay the data to remote servers via internet using the on-board wireless communication module. It is configured as a MQTT broker which maintains the topic list and subscription list of the clients. In addition, MQTT client can also be run on the same system to carry out on-board real-time analysis using the data gathered from the sensor nodes. The limitation of this work, and our logical next step, is the validation of the RMWSN. We will conduct device-level and device-on-human validations to address the functionality, performance (accuracy, reliability, data transmission, latency, etc.), and usability. The future work will include the development of accurate and robust real-time process/analysis algorithms and predictive models, leveraging statistical and/or machine learning methods.

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