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Wireless Battery-free Body Temperature Sensing Device for Key Workers

Amin Rigi [1], Andrew J Mugisha [1], Ahmed Arefian [2], Sadeque Reza Khan [1] and Srinjoy Mitra [1]

[1] *School of Engineering University of Edinburgh, King's Building Edinburgh EH9 3FF, UK*

[2] *Medzilla Ltd, Edinburgh, EH4 2TR, UK*

Abstract— We propose a battery-free temperature monitoring device that can be fitted inside the ear for an accurate body temperature measurement of a subject. The proposed application consists of 2 primary systems: (i) a battery-free temperature sensing Ultra High Frequency Radio Frequency Identification (UHF RFID) sensory tag and (ii), an auxiliary energy harvesting system, which enhances the sensing device's measurement accuracy and precision. The system can record changes in the localized body temperature of authenticated users with an average latency of 501ms. The assembly demonstrated a temperature average accuracy of ± 0.14 °C operating at 866 MHz. The system performance demonstrated high stability and repeatability of reported temperature measurements. The device's dimension is a form factor that can easily fit in a front shirt pocket, with a wire tethered earbud temperature sensor. The system is developed to make sensor measurements without requiring a battery for the device. Measurements are made remotely as users pass by checkpoints installed throughout a building. The device is a cost-effective solution for monitoring body temperature in work environments.

Index Terms— Battery free sensor, monitoring COVID-19 symptoms, energy harvesting, localized body temperature, remote sensing, UHF RFID, wireless connectivity.

I. INTRODUCTION

COVID-19 has transformed the norms of physical interaction in all walks of life, but the most among key workers. Key workers in hospitals, public transport, warehouses, postal system, supermarkets, the homeless, and other charities, schools, etc., are extremely susceptible to infection. Though they need to be physically present at their workplace to keep the basic economy functional, these locations are rarely built with consideration of social distancing. An ability to continuously and remotely monitor temperature during a long and stressful shift, particularly under Personal Protective Equipment (PPE), would provide a helpful early warning of infection. Fever, one of the most common COVID-19 symptoms, manifests under 24 hours, post the onset of infection [1]. Early detection of the Core-Body Temperature (CBT) spiking minimizes the probability of a communicable disease spreading rapidly across communities. An application, which can accurately monitor, and record slight variations in CBT, can be utilized as an early warning system. In [2], the authors indicate that frequent, localized body temperature monitoring has become a norm, globally. The wearable CBT body temperature sensor needs to be unobtrusive and accurate enough for early indication of viral fever. Furthermore, the sensor should be extremely easy to use, immune to rough handling and require a low level of maintenance. This is essential for increased adherence in high-stress and crowded conditions that key workers operate in. Oral thermometers are not suitable for such continuous usage and pose an additional risk of infection. The commonly used Infrared Radiation (IR) temperature sensor has limited capabilities for the detection of early changes of body temperature [3], [4] and has further limitations with PPE and people in groups. Remote temperature monitoring devices (e.g., thermal imager) mostly require an operator and are not for continuous operation [5]. They either require line of sight access or an occluded facial view. Skin temperature is often a wrong marker for Core-Body Temperature, particularly if the environmental condition changes or the subject is within a PPE. In-ear temperature, particularly close to the tympanic membrane is still the best method to monitor Core-Body Temperature without being invasive [6]. While in-ear temperature sensor prototypes were developed in [7], [8], the devices utilized batteries and had large form factors. These devices are not suitable for comfortable prolonged usage (e.g.8-10 hour shifts) with PPE. Furthermore, discharged batteries are one of the primary

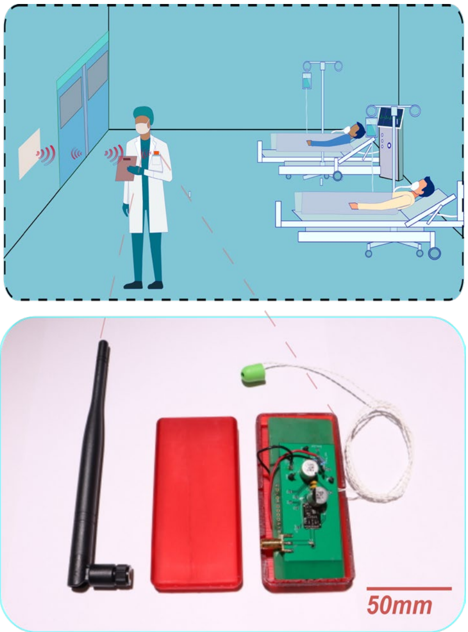

Figure 1: The use of the RFID sensing platform for constant body temperature monitoring (top image), The sensing platform components (bottom image)

corresponding author: Srinjoy Mitra (Srinjoy.Mitra@ed.ac.uk)

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reasons for non-functional electronic devices, and recharging (or changing battery) is an additional activity that the user has to remember. Hence, we propose a battery-free Ultra High Frequency Radio Frequency Identification (UHF RFID) based remote temperature sensing system. This would provide on-demand temperature monitoring for keyworkers, without any disruption to their routine activities. This low-maintenance, device will ensure higher user adherence. Furthermore, users can leave the device with their uniform or at the workplace and pick it up the next day ensuring regular usage. The FDA enforcement policy, "Enforcement Policy for Telethermographic Systems During the Coronavirus Disease 2019 (COVID-19) Public Health Emergency" recommends that the devices used for measuring body temperature have an accuracy of less than ± 0.5 °C in the temperature range of 34-39 °C [9]. The proposed RFID based in-ear temperature monitoring device is placed close to the tympanic membrane and can be fitted similar to a Receiver-In-Canal (RIC) hearing aid. The RFID sensor is powered up and multiple temperature readings are taken when the user walks within range of an RFID reader. Smart-phone sized readers can be fitted in multiple locations throughout a building (e.g., corridors, door frames). The user could either get a notification of their measured temperature by auditory feedback, i.e., beeps of different duration for normal and elevated temperature. There can be an RFID reader with a display at a secure location where the user could check the exact temperature and the trend. An illustration of the proposed application is shown in figure 1. The device can also be used for geo-tagging within a networked environment. This could help to identify the past movement trajectory of an infected person.

II. SYSTEM DESCRIPTION

Recent advancements have been made to realize wireless medical applications using RFID devices, particularly in the areas of remote sensing and monitoring, drug delivery, and implants [10]–[13]. In contrast to battery-assisted RFID tags, passive RFID systems are smaller in form factor but have less range. This is due to the limited energy harvesting capabilities of RFID tags [14]. Hence, available passive RFID sensing platforms have had limited commercial success due to low accuracy and dynamic range. In this work, we have developed a battery-free RFID body temperature sensing platform. The proposed pocket-sized application has been developed using Commercial Off-The-Shelf (COTS) components. RF energy, harvested by the application's energy harvester (EH) sub-system, is used to power a battery-free sensory UHF RFID tag. The sensory tag, in turn, activates and reads data from an external temperature sensor. The data is processed and wirelessly transmitted (backscattered) to a UHF RFID reader. Detailed block diagrams, illustrating the technical functioning of the application are illustrated in figure 2. A user can be uniquely detected by a reader station, within a range of around 1m.

In our proposed device, for high accuracy, precise and stable measurements, a miniaturized external temperature sensor was used. The temperature sensor is connected to a custom flexible 3D printed earplug and can be comfortably inserted into the ear. This COTS-based temperature sensing and monitoring application is an affordable device that can be easily integrated into healthcare networks. Since it will be expected for keyworkers to use this throughout their shifts, the device should not block the passage of natural sound. It is also expected that this device should be small enough to be used with a stethoscope or headphones.

III. ELECTRONIC DESIGN

We have developed a platform that harvests energy separately from the UHF RFID tag and provides a stable power supply of 3.24 V to a temperature sensor. The sensor along with associated circuits require a maximum 59 uA of current. The proposed device can supply the

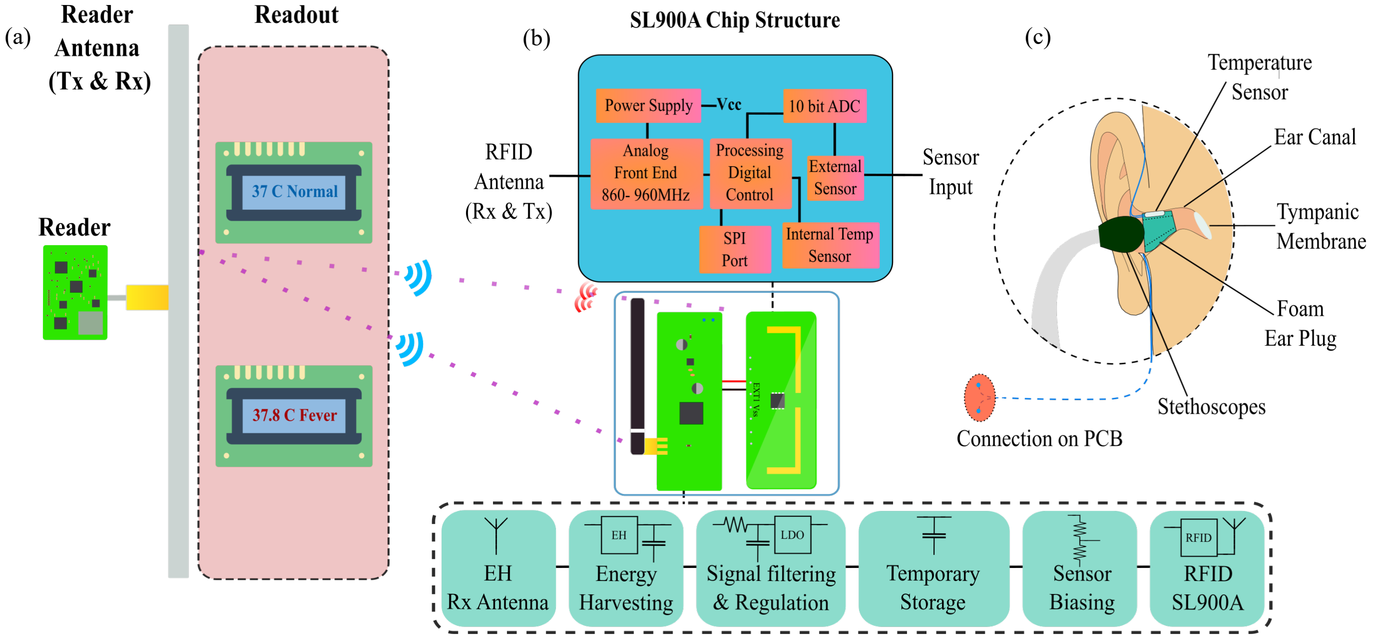

Figure 2: Battery free temperature sensor system layout (not to scale) **(a)** RFID reader system and readout **(b)** RFID tag with energy harvesting and sensing system **(c)** Demonstration of an in-ear application along with a stethoscope

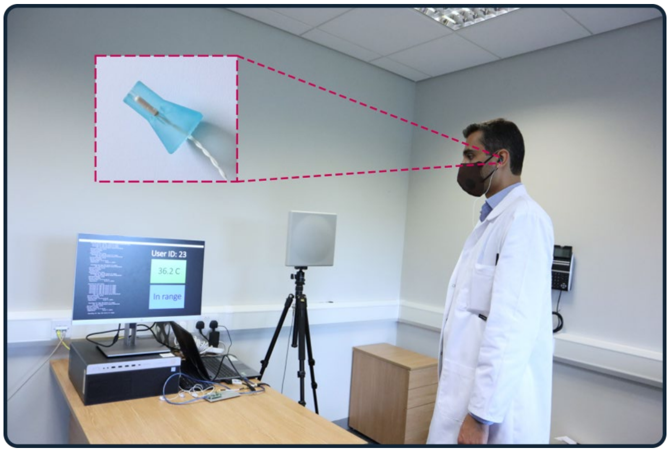

Figure 3: System setup showing sensing system, reader, antennas, and test setup

necessary power within 1m distance from the Reader Antenna. The RFID tag has a form factor of 180 x 30 x 60 mm^3 and can fit in a front pocket of a standard uniform (e.g, scrubs, factory overall). The device including the ear plug has a total weight of 120 grams. The length of the wire connecting the temperature sensor to the interface electronics can be maximum 90 cm. This is long enough for all adult bodies and will not create any additional discomfort.

To build a wireless, battery-free rapid temperature monitoring device, several elements have been integrated together to form the sensing platform. The SL900A RFID chip (data acquisition, signal modulation, and data transmission), a whip antenna, a low pass filter, and an energy harvesting unit as shown in the illustration in figure 2(b), constitutes the sensing platform. Furthermore, a reader (RFID-Reader PUR-RMCU-500U Beta) is used to transmit power wirelessly in the UHF RFID band and to receive the backscattered sensor data and user identification code (figure 2 (a)). The temperature sensor chosen has been exclusively designed for biomedical applications. The Amphenol Advanced Sensors device (MA100GG103AN) provides an extremely low tolerance of ± 0.075 °C for measurements ranging from 20 to 42 °C. The sensor has a small form factor of 9.52 x 2.03 mm, suitable for in-ear implementations. To provide good contact and movement stability the sensor is attached to a hollow custom-built earplug. The MA100 sensor is a Negative Temperature Coefficient (NTC) thermistor that shows a reduction in resistance with the increase of the temperature. The thermistor has a resistance of 10 kΩ at room temperature. The NTC sensor is part of a voltage bridge, where the overall output connects to the Analog to Digital (ADC) pin of the SL900A. The SL900A has an antenna pad sensitivity of -15 dBm when externally powered and reaches -6.9 dBm with no power source.

RFID antennas are designed to have strong backscattering properties and therefore are not ideal energy harvesting devices; thus, a separate antenna was implemented for the energy harvesting section. Our energy harvesting module consists of a Powercast Receiver P1110B chip which picks up the transmitted RF signal and converts it to a DC voltage. The system fluctuations are stabilized through a low pass filter, an LDO, and a capacitor to temporarily store the harvested energy providing a constant 3.24 V output. The 10-bit ADC sensing pin of SL900A, has a maximum input voltage of 0.7 volts, therefore the voltage input to the pin from the sensor was adjusted at 0.56 V for room temperature with a voltage divider using a 47kΩ resistor (increase of temperature results in voltage reduction). The sampled signal is then modulated and transmitted back to the reader as shown in the chip structure in figure 2 ((a), (b)). The PUR-RMCU-500U Beta reader was connected to a 9 dBi Beta layout UHF reader antenna, RK-10546 (figure 2(a)), to transmit data to and receive backscattered data from the SL900A chip. The energy harvesting antenna is a 3 dBi whip antenna operating between 860-960 MHz with a central frequency of 868MHz. As the user passes by an RFID reader, the system can provide auditory output to the users for notification of their body temperature rise, the system setup has been shown in figure 3. Since the harvested voltage can be monitored on the RFID tag and the reader, the user can also get an auditory notification if they are close but not within the optimal distance of the reader. To check the exact temperature, the user needs to come close to a Reader that also has a display. These can be placed in secure isolated locations to enable privacy. The user can verify their Tag ID on the display to confirm that they are not seeing a spurious reading. Furthermore, the environmental temperature can be measured and used to identify changes in body temperature influenced by changes in the surrounding environment. Moreover, monitoring the trend in multiple users will show such changes as all body temperatures might rise or fall to a certain degree based on environmental changes. All of these capabilities are possible with the excess power harvested within a one-meter range, beyond the requirement of the basic temperature sensing.

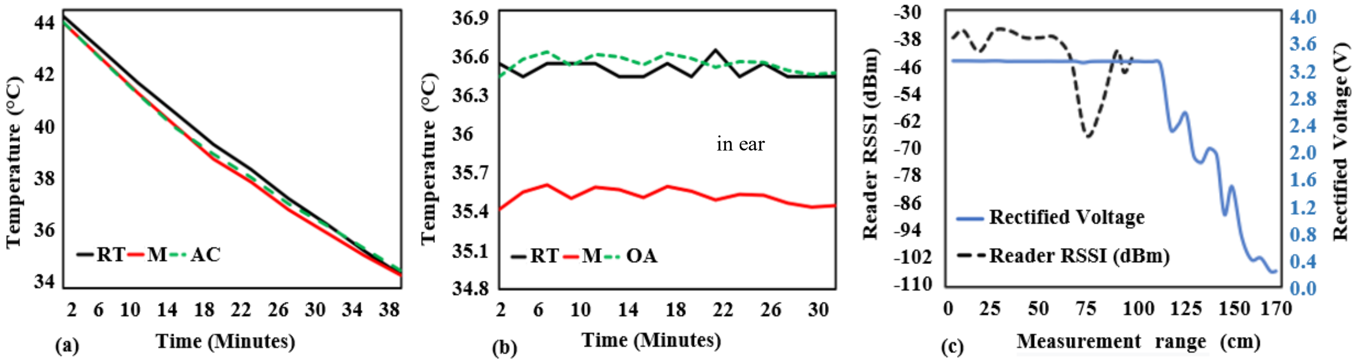

Figure 4: RT: Reference Temperature, **M:** Measured, **OA:** Offset Adjusted, **AC:** After Calibration **(a)** Temperature measurement made by reference device as a benchmark and our proposed device (DUT) in water **(b)** Measurements over a period of 30 minutes in ear **(c)** Harvested energy level and RFID's RSSI with the increase of distance

IV. EXPERIMENTAL SETUP AND RESULTS

A set of experiments were conducted to monitor the performance of the overall system. In the experimental setup, the reader and the sensing unit were set apart, without any obstacles in between them. The reader constantly transmitted RF signals to power up the energy harvesting module and received signals from the RFID tag. The reader then received the backscattered signals consecutively to accurately record measured values. The backscattered signal from the RFID tag consists of the user's identification code and the external sensor's measurements. An industrial temperature sensor (Elitech RC-4) was used to benchmark the performance of the proposed system. Both temperature sensors were placed in hot water which was let to cool. The error of the device was measured at different temperatures as shown in figure 4.(a) in which the temperature of hot water was measured both with the proposed device and the industrial temperature sensor. Measurements were taken from our full sensing system every minute while the water was cooling down and both readings were plotted in figure 4(a). After calibration the proposed sensor the device showed an average accuracy of ± 0.14 °C. The system was responsive up to 98 cm after which the RFID tag was no longer detected.

To further test the function of the device it was placed in the ear of the subject, and temperature readings were made every minute for 30 minutes (figure4(b)). A hospital standard infrared ear thermometer (Braun-Thermoscan 7- IRT6520) was used for reference body temperature measurements from one ear while the proposed sensor measured temperature from the other ear. Compared to water-bath measurement, we noted an offset of 1°C (figure 4(b)) for in-ear measurement. This was due to the unidirectional heat transfer within the ear-plug and can be adjusted by calibration. The average precision of the in-ear test was ± 0.087 °C. The system's response time was 501ms which was measured over 15 measurements where the user entered the detection area from different angles. This is fast enough for a user to take a quick measurement by briefly standing in front of a reader station.

To further examine the measurement repeatability and accuracy, an experiment was conducted with 5 subjects, both male and female (age 22-42). The device showed an average precision of 0.064°C within 10 separate measurement cycles. While using Braun-Thermoscan as the reference, the average accuracy was observed to be 0.63°C and the lowest accuracy was 1.5°C. This can be attributed to participants having different ear shapes and the current earpiece did not always fully fit into the ear, exposing part of the sensor to the surrounding air temperature. Repeated measurements for the same user showed that the error acts as an offset. The average accuracy after offset adjustment was 0.22 C. A part of future work would be to improve the design of the earplug including multiple sized versions.

The system was used by a medical doctor to investigate the application of a stethoscope while the sensor is in the ear. While the stethoscope could be used with the sensor without much discomfort, it led to a reduction of sound in one ear. On the other hand, headphones were successfully used with the device to ensure functionality for factory workers for multitasking purposes.

Figure 4 (c) Shows the harvested energy voltage level and RFID tag's Receiver Signal Strength Indicator (RSSI) with the increase of distance between the reader antenna (Tx) and the sensing device. The RSSI indicates that the received signal is not strong enough to reach the reader beyond 98 cm of range. However, harvested voltage levels provide evidence of a 113cm range for the energy harvesting setup.

V. CONCLUSION

The proposed RFID (Radio-frequency identification) based in-ear temperature sensor for constant symptom monitoring of key workers showed promising results for constant and remote monitoring of body temperature. This is essential for early-stage detection of Covid-19 symptoms and eventual isolation. The unobtrusive, battery-free device is expected to increase user comfort and adherence. Such a device can overcome many of the shortcomings of other temperature monitoring devices thus enabling high accuracy rapid measurements with no additional workload. With the proliferation of temperature measurement norms in various public places (restaurants, universities, theatres etc.), we expect such a device to be useful for the general population as well.

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