Wearable device prototype for vital signs monitoring

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***Abstract*—Monitoring vital signs is a basic need in healthcare institutions. Due to the limited capacity of these facilities, wearable devices have emerged aiming to aid ambulatory monitoring and doctors' daily activities. This work presents the proof of concept of a wearable device for non-invasive real-time vital signs monitoring. The prototype comprises an MSP432P401R microcontroller, an HC-06 Bluetooth module, and an SEN-15219 biometric sensor board. This device acquires and wirelessly transmits photoplethysmography signals, heart rate, and blood oxygen saturation level, featuring an autonomy of almost 40 hours.**

***Index Terms*—long-term monitoring, photoplethysmography, PPG, heart rate, blood oxygen saturation, SpO2**

I. INTRODUCTION

The top global causes of death are associated with three broad topics: cardiovascular (ischaemic heart disease, stroke), respiratory (chronic obstructive pulmonary disease, lower respiratory infections), and neonatal conditions [1]. The treatments for these diseases rely on daily monitoring of vital signs. Moreover, the need for ambulatory low-cost medical equipment to give quick, continuous, and remote access to physiological parameters to improve communication, diagnosis and treatment, is increasing [2], [3].

Monitoring heart rate (HR), blood pressure, temperature, and blood oxygen saturation level (SpO2) are fundamental in the physiological assessment of a patient. The photoplethysmography (PPG) signal is employed to obtain these parameters non-invasively, as stated by Webster [4] for different diagnostic applications. This technique uses a light source capable of transmitting different wavelengths and a photodetector. The light transmitted is absorbed, and then it is spread over human tissue. The reflected light variation corresponds to blood volume changes (known as plethysmography) [4].

The literature reveals several works addressing the development of vital signs monitoring wearable devices using PPG. Such as low-cost devices aiming at non-medical markets like daily activity or sports routine monitoring [2]. Although there are indications that these devices could have a medical grade in the future [5], commercially available solutions are usually not intended for medical use [6], [7]. It is also possible to see mobile healthcare devices from medical device companies [8], [9]. Finally, it is feasible to find open-source alternatives [10] and research efforts [11], [12].

This work introduces the proof of concept of a wearable device that acquires PPG, HR, SpO2 and temperature. The device wirelessly transmits these parameters in real time to a personal computer (PC), where a graphical user interface aimed for research and development runs (see Fig. 1). In the future, the system will also show the vital signs on a display located in the wearable device.

II. PROPOSED SOLUTION

The system consists of 4 stages (see Fig. 1): data acquisition (HR, SpO2, temperature, and PPG), data processing, data transmission via Bluetooth (BT) link, and data visualization.

A. Hardware

Fig. 1 shows the hardware elements of the solution and their interactions.

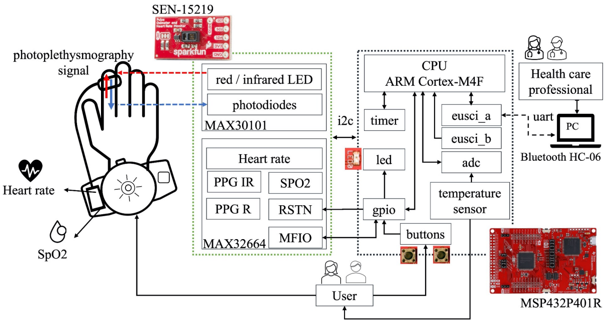

Fig. 1. Block diagram of the vital signs monitoring system.

The SEN-15219 board from SparkFun performs the acquisition of HR, SpO2, and PPG raw data. This board consists of an analog front-end (MAX30101) and a sensor hub (MAX32664), both chips from Maxim Integrated. The MAX30101 has three sensor LEDs: a red one (R), an infrared one (IR), and a green one. When users place their index finger on top of the LEDs, photodiodes capture the reflected light emitted by the LEDs and, therefore, the PPG data. The MAX32664 internally calculates the HR and SpO2 values using the PPG with an accuracy that would comply with the FDA standards [13] and transmits them using the I2C serial protocol.

MSP432P401R from Texas Instruments is a 32-bit ARM-Cortex M4F microcontroller with a hardware floating-point unit. It was configured to work in two modes: i) low power mode 0 (LPM0) to save energy during the wait times in communication with the SEN-15219 board; and, ii) active mode at 48 MHz. It communicates with the SEN-15219 board using I2C at 400 kHz and the HC-06 BT module using UART (Universal Asynchronous Receiver-Transmitter) at 115200 bps. Temperature is obtained using the microcontroller's internal sensor.

B. Embedded software

The embedded software follows a Function-Queue-Scheduling architecture [14]. Interrupt service routines (ISR) add function pointers (tasks) to a queue while the main loop reads these pointers from this queue. Thus, the corresponding queued function is called. This architecture allows the definition of low and high-priority tasks separately (like alarms management and data acquisition).

Fig. 2 illustrates the workflow followed by the embedded software. After system initialization, which includes the configuration of the SEN-15219 board and microcontroller peripherals, the device enters LPM0. Then, the embedded system performs the same tasks periodically. Every 40 ms, it obtains PPG (samples of IR and R), HR, and SpO2 data from the SEN-15219 board. When 200 ms elapsed, it sends PPG signal values to the BT module, that are forwarded to the PC for real-time visualization. Finally, every 1 second, it acquires and sends HR, SpO2, and temperature to the PC.

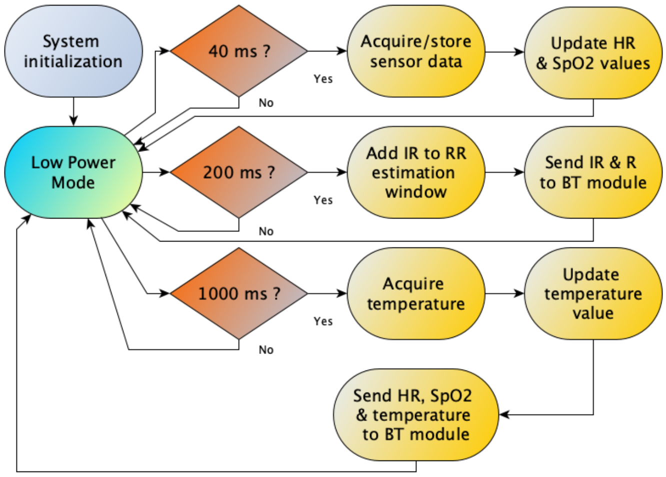

Fig. 2. Embedded software workflow

The configuration of the SEN-15219 board consists of enabling its output mode to acquire the PPG signal (MAX30101) and enabling the internal algorithm for calculating HR and SpO2 (MAX32664). The embedded software initializes the MAX32664 with a data rate of 100 samples per second (in 24-bytes data frames) and parses these frames obtaining the raw data, the parameters, and a status byte.

The system uses ISRs to handle the peripheral data. The MSP432P401R has a nested vector interrupt controller that permits setting priorities for each ISR. EUSCI-B (Enhanced Universal Serial Communication Interface) was configured for I2C communication protocol with the SEN-15219 board with the highest priority. This configuration ensures that the microcontroller obtains the data from the SEN-15219 board timely. The other peripherals that use ISRs are the General-Purpose-Input-Outputs (GPIO) for buttons, the TIMER-A for timing tasks, ADC for temperature acquisition, and the EUSCI-A used in UART mode for interfacing with the BT module. The system configures all these ISRs with low priority.

III. EXPERIMENTAL RESULTS

Fig. 3 shows the test setup used for the experiments.

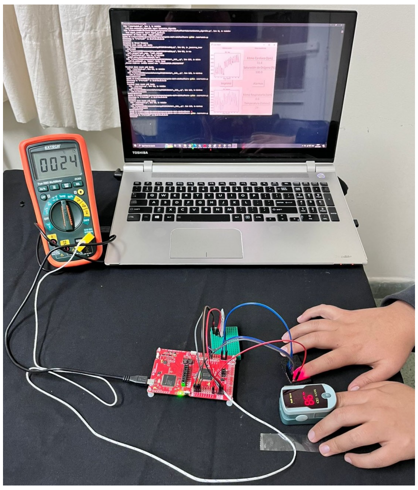

Fig. 3. Wearable device prototype under testing

A. Energy Consumption and autonomy

The energy consumption was measured considering two operation modes: i) *continuous mode*, where the device acquires data and transmits them to a PC; ii) *intermittent mode*, where every 256 seconds, a timer wakes the system up from low power mode 3 (LPM3) to acquire data and transmit them for 30 seconds.

We measure the RMS current drained from the power supply using a standard 3.5-digit multi-meter and *Energy Trace* from Texas Instruments. Table I shows energy consumption and autonomy. The autonomy was determined considering a 235 mAh coin cell lithium CR2032 battery.

TABLE I
ENERGY CONSUMPTION AND SYSTEM AUTONOMY (IF POWERED BY A 235 MAH BATTERY)

Operation Mode	Energy (mWh)	Battery Life (HH:MM)
Continuous	136.3	05:11
Intermittent	17.8	39:37

The most power-hungry component of the system is the SEN-15219 board. In the continuous mode with a finger over the LEDs sensor, the SEN-15219 board consumes 86 mWh (63.1 %). It has a baseline energy consumption of 26.2 mWh (19.3 %) when the chips are off. The LEDs sensor consumes 40 mWh (29.4 %), and the rest of the board consumes 19.6 mWh (14.4 %). On the other hand, the HC-06 module consumes 43 mWh (31.6 %) and the microcontroller 7.3 mWh (5.3 %).

The system allows almost 40 hours of intermittent monitoring which can help to store enough data if needed by the physician.

B. Memory usage

Memory usage was measured using *Code Composer Studio* from Texas Instruments. Table II shows these results.

TABLE II
MEMORY USAGE

	Flash (kB)	Flash (%)	RAM (kB)	RAM (%)
Available	256	100	64	100
Used	6.9	2.7	36.1	56.2

C. Vital signs measurement

Experimental evaluation was performed on a healthy young adult (female, 26 years old) in a quiet room in a home environment. The test subject was instructed to synchronize her respiration rate with a constant rhythm provided by a metronome.

Table III shows results from the experimental evaluation using the prototype (Device) and its comparison with values obtained using the CE-certified pulse oximeter CMS50D from Contec Medical Systems. The Mean Absolute Error (MAE) and Relative Error of the measurements are low and acceptable for the targeted application.

TABLE III
DEVICE MEASUREMENTS

	Heat Rate (bpm)			SpO2 (%)		
Test	Ref	Device	Rel. error	Ref	Device	Rel. error
1	75.0	74.5	0.67%	94.0	94.7	0.74%
2	71.0	70.5	0.71%	94.0	95.4	1.47%
3	68.0	68.4	0.58%	94.0	96.6	2.69%
4	67.0	69.4	3.46%	94.0	93.8	0.21%
5	68.0	68.6	0.87%	95.0	95.6	0.63%
6	73.0	75.1	2.80%	93.0	93.6	0.64%
7	69.0	70.9	2.68%	96.0	96.8	0.83%
8	71.0	71.8	1.11%	96.0	98.0	2.04%
9	68.0	69.4	2.02%	96.0	96.1	0.10%
10	72.0	71.2	1.12%	98.0	97.1	0.93%
MAE	1.14			0.99		

D. Comparison with other solutions

Table IV summarizes the main characteristics of our system compared to other devices (prototypes and commercial products). A fair comparison between such different implementations is difficult. Nevertheless, this qualitative comparison shows the potential of our proposal and locates our prototype within the state-of-the-art. All considered solutions present the sensor inside a fingertip case. The comparison shows that our prototype performs well in line with other systems while providing low cost and a potential FDA approval.

IV. CONCLUSIONS

The prototype of a low-cost device has performed real-time acquisition of relevant vital signs in a non-invasive way. It has also achieved the wireless transmission of these signs to a PC, featuring an autonomy of almost 40 hours. The prototype performs well if compared with similar commercial products. It provides relatively high battery life and could be potentially indicated for clinical usage.

Our following steps include incorporating respiratory rate estimation into our device using already acquired PPG data and conducting more experiments. In addition, we are planning to add a display, decrease power consumption by using BLE (Bluetooth Low Energy) instead of BT, incorporate the MAX30101 and MAX32664 into a custom PCB, and reduce the system's overall size to develop a suitable case.

TABLE IV
COMPARISON WITH OTHER WEARABLE DEVICES WITH FINGERTIP CASE

	Nonin [8]	Masimo [9]	Uguz [11]	This work
Parameters	HR, SpO2	HR, SpO2 PPG	HR, PPG, Temp	HR, SpO2 PPG, Temp
Connectivity	BLE	BLE	Wired	BT
Autonomy	44 hs	15 hs	N/A	39.6 hs
Power source	Alkaline AAA (x1)	Alkaline AAA (x1)	N/A	CR2032 (x1)
Size	56x74 mm	41x71 mm	N/A	N/A
Weight	71 g	73 g	N/A	N/A
Clin. approval	Yes	No	No	Potential
Cost	$969	$299	N/A	N/A
Status	Commercial	Commercial	Prototype	Prototype

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REFERENCES

[1] WHO. (2020, 12) The top 10 causes of death. Accessed September 2021. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/the-top-10-causes-of-death

[2] M. A. F. Pimentel, A. E. W. Johnson, P. H. Charlton, D. Birrenkott, P. J. Watkinson, L. Tarassenko, and D. A. Clifton, "Toward a robust estimation of respiratory rate from pulse oximeters," *Eng. IEEE Trans. Biomed. Eng.*, vol. 64, no. 8, pp. 1914–1923, 2017.

[3] J. Oreggioni, A. A. Caputi, and F. Silveira, "Biopotential monitoring," in *Encyclopedia of Biomed. Eng.*, R. Narayan, Ed. Oxford: Elsevier, 2019, pp. 296–304. [Online]. Available: https://www.sciencedirect.com/science/article/pii/B9780128012383641612

[4] J. G. Webster, *Design of pulse oximeters*. CRC Press, 1997.

[5] S. H. Browne, M. Bernstein, and P. E. Bickler, "Accuracy of samsung smartphone integrated pulse oximetry meets full FDA clearance standards for clinical use," *medRxiv*, 2021.

[6] Apple. (2022, 06) Apple Watch Series 7. [Online]. Available: https://www.apple.com/apple-watch-series-7/

[7] Samsung. (2022, 06) Galaxy Watch3. [Online]. Available: https://www.samsung.com/latin/watches/galaxy-watch/galaxy-watch3-45mm-mystic-silver-sm-r840nzsalta/

[8] Nonin. (2022, 01) WristOx2 Model 3150 with BLE. [Online]. Available: https://www.nonin.com/support/3150-ble

[9] Masimo. (2022, 01) MightySat. [Online]. Available: https://www.masimopersonalhealth.com/pages/mightysat

[10] HealthyPi. (2021, 09) Welcome to HealthyPi v4. [Online]. Available: https://healthypi.protocentral.com/

[11] D. Uguz, "Design of a multipurpose photoplethysmography sensor to assist cardiovascular and respiratory diagnosis," in *21th Int. Student Conf. on Elect. Eng.*, vol. 21, 2017, pp. 1–7.

[12] F. Braun, P. Theurillat, M. Proença, A. Lemkaddem, D. Ferrario, K. De Jaegere, C. Horvath, C. Roth, A.-K. Brill, M. Lemay, and S. Ott, "Pulse oximetry at the wrist during sleep: Performance, challenges and perspectives," in *42nd Annu. Int. Conf. of the IEEE Eng. in Med. Biol. Soc.*, 2020.

[13] Maxim Inc., "Wearable optical measurement solution based on MAX32664," App. Note 7400, Tech. Rep., Mar 2021.

[14] D. E. Simon, "Survey of software architectures," in *An Embedded Software Primer*. Addison-Wesley Professional, 1999, pp. 115–136.