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Miniaturization of a Finger-Worn Blood Pressure Instrument

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Abstract— Blood pressure monitoring using a traditional arm cuff device is often inconvenient and possibly painful. We present a miniature cuffless tonometric finger probe system, that uses the oscillometric method to measure blood pressure (BP). A small enough device could be used for convenient ambulatory measurement and be worn during sleep with minimal discomfort. In addition to BP, the device is able to collect arterial pulse wave data that can further be used to derive other cardiovascular parameters, such as heart rate (HR), heart rate variability (HRV) and central aortic systolic pressure (CASP). The device uses a motor controlled press that is used to apply pressure to the finger tip to measure the oscillometric response. We verified the functionality of the device by proof-of-concept measurements. Lastly we evaluate methods for further developing the concept and discuss the future directions.

I. Introduction

Elevated BP is one of the leading causes of death globally and one of the most important modifiable risk factors for adverse cardiovascular events, yet it is severely under-monitored [1]. Uncontrolled high BP can lead to disability, poor quality of life and fatal heart attack or stroke [2]. With changing global lifestyle, hypertension affects people at increasingly younger age and frequency [3]. Currently, the trend in BP monitoring devices is going towards wearable technologies and ease-of-use. Healthcare professionals also recommend the blood pressure to be monitored more regularly and frequently instead of random spot checks [4].

In our previous study we presented a tonometric instrument for measuring blood pressure from the fingertip [5]. Operation of the device was validated (n=33) against an automated arm cuff device (Omron M3) resulting in systolic (SBP) and diastolic (DBP) pressures (($mean \pm SD$) mmHg) of (-0.9 ± 7.3) mmHg and (-3.3 ± 6.6) mmHg, respectively. CASP measurements (n=5) were compared against a pulse wave analysis (PWA) device (Atcor Medical Sphygmocor XCEL) revealing central aortic systolic pulse (CASP) and central augmentation index (cAIx) estimates with precision and accuracy of (2.0 ± 3.7) mmHg and (1.4 ± 6.2)% respectively.

In this study, we further advance the concept and develop a miniaturized version of the device, similar to traditional pulse oximeters. The device should be unobtrusive, so it could be used for extended periods, e.g. during sleep. Many wearable BP instruments use pulse wave propagation or pulse wave analysis methods to measure BP [6]–[8]. These devices often require initial arm cuff calibration to be made via a brachial cuff device. Our device relies on the oscillometric method to acquire spot BP measurements [9]. Similar techniques have been introduced before but the require a bulky external pneumatic unit for pressure generation or they rely on user actuation [10]–[12]. A common issue with a cuff-based approach is that the cuff size is often optimal only to a limited number of subjects.

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II. Methods

A. Electronics

The system is built around the nRF52840 USB dongle, which houses an ARM Cortex M4 based microcontroller unit (MCU) by Nordic Semiconductor along with the necessary peripherals to run the MCU [13]. A barometric pressure sensor (Bosch Sensortec BMP 180) is connected to the MCU via I^2C connection [14]. A DC motor is used to apply pressure to the finger. The MCU is interfaced to the motor via an H-bridge circuit that enables bidirectional motor control. In order to make sure the pressing device does not move out of its range, the hinge is equipped with limit switches for the lower and upper boundaries. This also prevents possible injuries that could be caused by excessive pressure to the finger. The MCU is connected to a laptop computer via USB.

B. Software and algorithms

The device firmware was written in C programming language using the nRF5 software development kit (SDK). The main functionalities of the firmware are sampling the pressure sensor and controlling the pressure-generating motor. The sampling is performed using timer interrupts occurring at regular intervals. The timer is run on a high-frequency clock to guarantee an accurate sampling rate. During each timer interrupt the pressure sensor is read and the pressure value together with a timestamp is sent over to a computer using a virtual serial port. The pressure value is then compared to a predefined maximum pressure value set above the expected systolic blood pressure. If the maximum pressure value or the upper limit switch has been reached, the motor, controlled with pulse-width modulation (PWM), is reversed and run until the lower limit switch has been reached.

The device firmware is controlled with a graphical user interface (GUI) written in Python. The application connects to the device through a USB serial connection,

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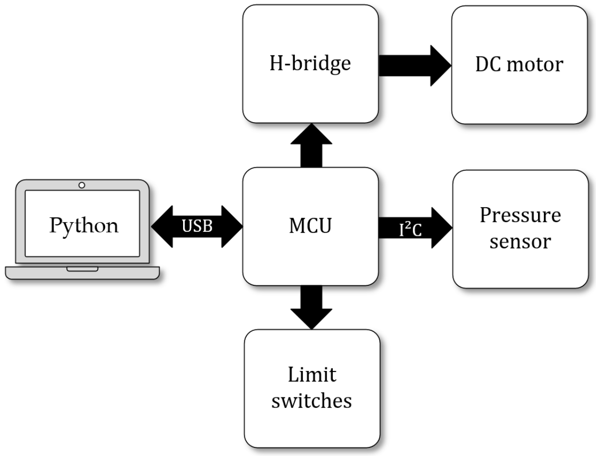

Fig. 1. System block diagram. An ARM Cortex M4 based MCU is used to control the peripherals. The MCU is connected to a laptop running a Python GUI for data logging.

which is used to send commands and receive data. The application plots the incoming data in real-time and uses Python's multiprocessing package to isolate the data process from the main process. The user interface allows the user to change the settings of the device, such as the speed of the motor and the maximum allowed pressure, and to control the measurement process. Once a measurement has been completed, the received data together with the used device settings are stored as a comma-separated values (CSV) file.

Post-processing is performed on MATLAB. i) Atmospheric pressure is subtracted from the signal. ii) The data are filtered with a pass-band of 1 to 10 Hz and the filtered signal is Hilbert transformed. iii) A peak detection algorithm followed by polynomial fitting is applied. The resulting bell-shaped curve is called oscillometric waveform envelope (OMWE). Mean arterial pressure (MAP) is found at the point on the pressure curve that corresponds with the maximum of OMWE. SBP is the pressure point at 70% of the maximum on the high pressure side and DBP at 40% on the low pressure side.

After the oscillometric measurement, the external pressure is adjusted to MAP enabling maximal pressure coupling from the artery to the sensor. A recording of 1 minute is made at MAP. First the signal is band-pass filtered, then convoluted with a triangular wavelet. The convolution step smooths the signal without distorting the time intervals. Peaks are detected from the smoothed signal and finally HR and HRV can be calculated. The algorithm pipeline is shown in Figure 4.

C. Mechanics

The mechanics of the instrument are built to house the electronic components and provide a method to apply controlled pressure to the finger. In addition, it provides a structural base for the tonometric pressure sensor. The enclosure was 3D printed using selective laser sintering (SLS) process. A standard pressure sensor is modified by prying off its protective metal lid and an air-filled cushion is placed on top of it. A cylindrical piston is placed on the cushion and acts as the tonometer probe. The piston consists of two pieces attached together from the ends of a threaded shaft, enabling piston extension and distension in case the protrusion height of the piston has to be adjusted. A DC motor followed by a reduction gear train is placed in the inner supporting enclosure. A worm gear assembly further reduces rotational speed and changes the angle of rotation. The whole transmission is encased in an inner support structure. A hinge-type press system is used to apply pressure to the finger. The portion making contact to the finger is made from a soft 3D printing filament. Figure 3 clarifies the mechanical design of the device.

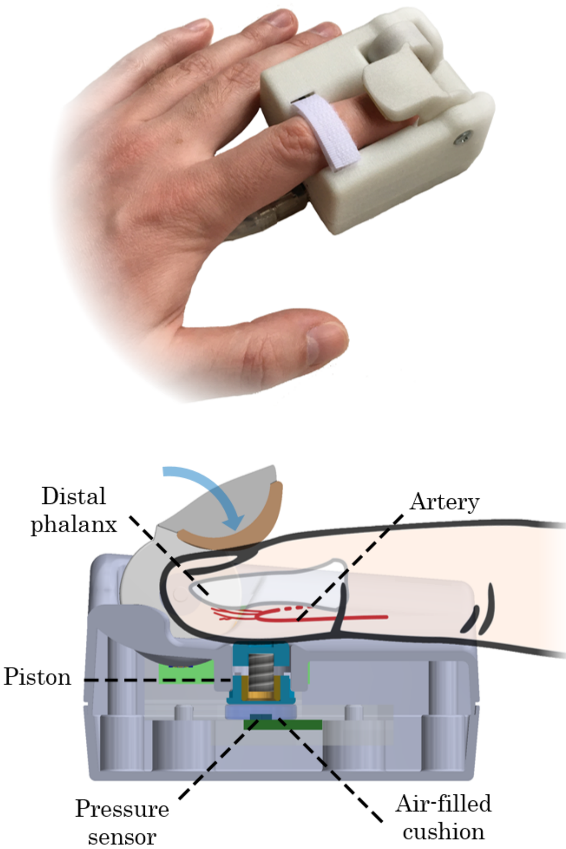

Fig. 2. A picture of the device in use (top) and sensor operation (bottom). A velcro strap provides additional support to the finger. A standard barometric pressure sensor (Bosch BMP180) is customized by removing the metal packaging and placing an air-filled cushion on top of it. A two-piece piston construction is placed on top of the cushion ensuring that the pressure is directed correctly. The target artery is distal transverse palmar arch (DTPA) artery located in the fingertip just under distal phalanx.

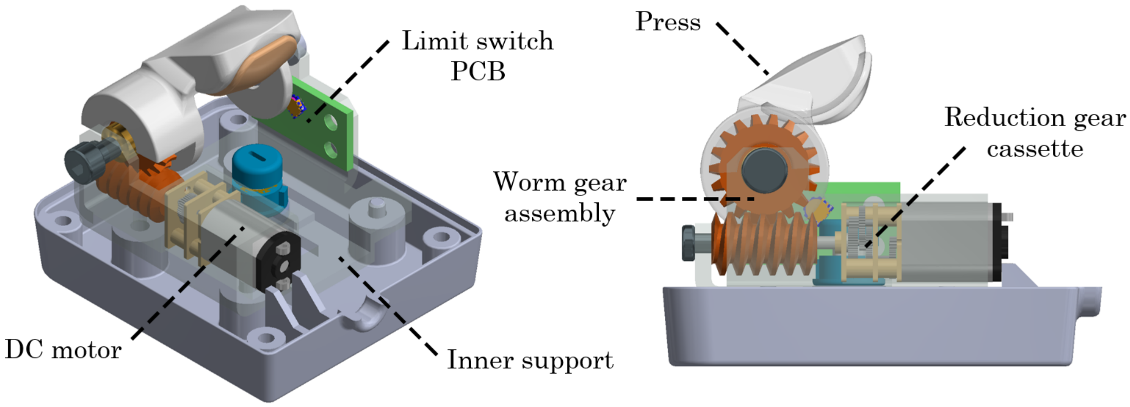

Fig. 3. 3D model showing the torque transmission. A DC motor is connected to a worm gear assembly through a reduction gear cassette. This rotates a hinge-type press that is used to apply pressure to the finger. A pair of micro limit switches assembled on a custom PCB (printed circuit board) is used to restrict the motion.

III. Results

A. Operating principle

The technology relies on a custom built tonometric sensor setup shown in Figure 3. The assembled device is shown in Figure 2. The tip of the finger is placed on the piston and a force is applied to the finger via the rotating press. The pressure fluctuation in the distal palmar arch artery located in the fingertip is coupled to the pressure sensor via the air cushion. Anatomy of the fingertip is shown in Figure 2. The internal pressure of the cushion matches the pressure exerted to the finger. At MAP, the arterial and cushion pressure are equal.

B. Oscillometric method

We have previously shown that the tono-oscillometic setup is suitable for BP monitoring and in the current study we present proof-of-concept measurements mainly for technical verification [5]. Both decreasing and increasing sweeps were made, starting from and stopping at supra-systolic pressures respectively. Figure 4c shows an example measurement resulting in SBP of 128 mmHg, MAP of 87 mmHg and DBP of 69 mmHg. The device performed well on oscillometric measurements, providing a steady pressure curve for increasing and decreasing pressure. Manufacturing tolerances were tight since no twitching, which was an issue in some earlier prototypes, was perceived.

C. Heart rate

We applied signal processing methods to the 1 minute finger pulse data recorded at MAP. A sample measurement is shown in Figure 4. The measurement was started normally at rest and followed by deep breathing starting at roughly 25 seconds. Heart rate variability (HRV) represents the variation of time between subsequent heartbeats. HRV is known to be linked to the respiratory cycle and it increases during deep breathing as seen in Figure 4b [15].

IV. Discussion

This study was essentially an extension to our previous study, where we introduced a table-top blood pressure monitor that could measure BP and assess cardiovascular health from the fingertip [5]. Here, we further refined the concept by miniaturizing the technology and developing a finger-worn wearable device for BP monitoring. The device performed well at the initial tests and we believe the technology could be used for long-term BP monitoring, such as the detection of nocturnal dipping during sleep. This phenomenon is found to correlate with the onset of cardiovascular disease more accurately than traditional office BP measurement [16].

Currently the device is powered and the data is collected via USB, making it necessary to be connected to a computer at all times. The enclosure still has space for a Li-ion battery and necessary charging circuitry. In the future we will investigate how the system performs in wireless mode. This introduces a challenge on power consumption and low-power design. Furthermore, a clinical trial according to a standard protocol would be beneficial.

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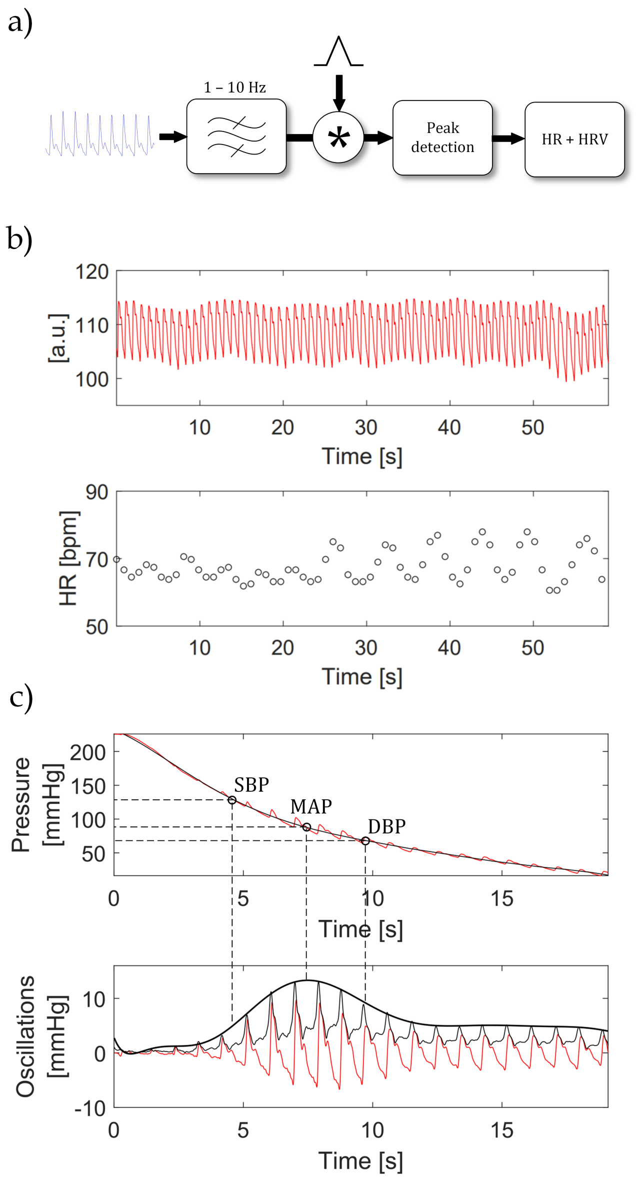

Fig. 4. a) Algorithm for HR extraction. First the 1 minute signal is band-pass filtered, then convoluted with a triangular wavelet. Peaks are detected from the smoothed signal and finally HR and HRV can be calculated. b) Heart rate variability perceived during a 1 min measurement. Deep breathing is applied at 25 s. Respiratory rhythm is clearly visible on the HR signal. c) Oscillometric BP measurement. The pressure is raised above SBP and slowly decreased below DBP. The oscillometric waveform envelope is formed by Hilbert transform, peak detection and linear fitting. MAP is marked on the upper curve at the corresponding point of oscillometric envelope maximum. SBP and DBP are calculated using pre-fixed percentages on the envelope.

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