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Clip-on Wireless Wearable Microwave Sensor for Ambulatory Cardiac Monitoring

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Abstract — We present a new type of non-contact sensor for use in ambulatory cardiac monitoring. The sensor operation is based on a microwave Doppler technique; however, instead of detecting the heart activity from a distance, the sensor is placed on the patient's chest over the clothing. The microwave sensor directly measures heart movement rather than electrical activity, and is thus complementary to ECG. The primary advantages of the microwave sensor includes small size, light weight, low power, low-cost, and the ability to operate through clothing. We present a sample sensor design that incorporates a 2.4 GHz Doppler circuit, integrated microstrip patch antenna, and microcontroller with 12-bit ADC data sampling. The prototype sensor also includes a wireless data link for sending data to a remote PC or mobile phone. Sample data is shown for several subjects and compared to data from a commercial portable ECG device. Data collected from the microwave sensor exhibits a significant amount of features, indicating possible use as a tool for monitoring heart mechanics and detection of abnormalities such as fibrillation and akinesia.

Index Terms — cardiac monitoring, wearable sensors, wireless, Doppler radar, heart rate, mobile sensors.

I. INTRODUCTION AND MOTIVATION

There is increasing need for ambulatory monitoring of physiology. The applications for these technologies are numerous, but several major applications include outpatient care, patient monitoring, physical therapy, elder care, sports/fitness training, emergency response, and long-term monitoring of various chronic health conditions [1]-[5]. The basic system requirements for these applications include: portability, low-power (for battery powered use), and relatively small size/weight. For applications requiring large-scale deployment, cost is an additional practical consideration.

For heart monitoring in particular, traditional approaches to long-term monitoring have included ECG devices [6]-[7] such the Holter monitor, which typically uses a 5-lead electrode bundle attached to the chest. While ECG is the preferred standard for portable

Fig. 1. Photograph of person wearing clip-on sensor. The sensor is designed to fit inside a common name badge plastic sleeve and attached over clothing.

cardiac monitoring, it is not always practical or preferable to attach electrodes to the chest, particularly in the case of women. Although electrically conductive fabrics and garments can be used as an alternative to ECG electrodes, these garments are not widely available and also require daily replacement and washing similar to other clothing garments.

While ECG measures the electrical activity of the heart, there is also interest in monitoring the physical motion and mechanics of the heart, including detection of abnormalities such as fibrillation and akinesia. In clinical settings, echocardiography is a powerful tool for studying heart mechanics, but this technology is not amenable to portable ambulatory monitoring.

Other portable devices for heart monitoring include photoplethysmography (PPG) [8]-[9] which does not monitor the heart per se, but instead measures the blood volume pulse in perfused skin. While PPG and optical methods do not require physical contact with the skin, optical access to perfused skin is still required.

Acoustic or piezoelectric devices also exist, which can acoustically monitor the sound of the beating heart when placed directly on the chest [10]. These devices also generally require direct acoustic coupling to the patient's chest.

In this paper, we present a new clip-on microwave sensor for use in ambulatory cardiac monitoring. Beyond simple heart beat detection we present sample

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data from the sensor, showing the mechanical motion of the heart which is not accessible by other portable measurement methods.

II. MICROWAVE DOPPLER DETECTION

The development of microwave Doppler radar for vital sign monitoring is relatively recent but fairly well-known [11]-[17]. The basic concept, shown in Figure 2, involves generating a very low power microwave beam that illuminates the heart. The outgoing beam and the Doppler-shifted reflected beam are mixed together to produce a very low frequency signal that is proportional to the physical motion of the heart. In the case of the wearable device, the phase shifted reflected wave is produced by the near-field electromagnetic interactions between the antenna and the pulsating cardiac and body tissues. However, the detection circuitry is identical in either case.

A perennial challenge of microwave Doppler sensors has been the difficulty of separating the heart signal from the gross physical motion of the person [18]. However, if the sensor is attached to the person, such that the sensor moves along with the person, then this problem is largely eliminated.

Published research in Doppler radar sensors [11]-[17] has primarily focused on detecting a beating heart from a distance (1-3 meters). As a result, these systems make use of laboratory-grade microwave equipment and antennas which are not portable, not small, and quite expensive. Other side of body can also be used [22]. The development of small low-cost Doppler radars for vital sign detection has been published only recently [19] but no data has yet been published investigating the use of this technology for use as a *wearable* sensor for ambulatory cardiac monitoring.

III. IMPLEMENTATION

A photograph of the completed Doppler radar unit is shown in Figure 3. Each subsystem is described below.

A. Microwave oscillator

A 2.45 GHz microwave oscillator was implemented using a single transistor (NTE65) oscillator circuit employing a microstrip resonator.

B. Microstrip Transformer

The microwave signal was coupled to the antenna using a microstrip coupled line transformer. This served to electrically isolate the oscillator circuit and also impedance match to the antenna.

Fig. 2. Simplified block diagram for monostatic Doppler radar unit, showing oscillator, antenna, and single mixer followed by baseband band-pass filter.

Fig. 3. Transparent plastic clip-on badge holder showing component side of microwave sensor board including integrated microwave circuit, patch antenna, filter, and microcontroller. (Radio link module and battery on reverse side)

C. Microstrip Patch Antenna

An edge-fed microstrip antenna was designed using Ansoft HFSS v11 software and designed for standard FR4 dielectric with $\epsilon = 4.2$. The completed antenna has a measured return loss of approx -18 dBm and directional gain of approx 4 dBi, with a half-power beamwidth of approximately 60 degrees.

D. Mixer

In order to minimize cost, a simple diode mixer was used (part #Avago 5082-2835). Since the distance between the antenna and the target is fixed, quadrature detection was not necessary. The optimal phase offset could be tuned and optimized simply by varying the connection point of the diode along the microstrip line.

E. Low-pass filter

The baseband filter section consisted of two 6-pole elliptic filter sections with zeros at 50 Hz and 60 Hz and a corner frequency of 100 Hz.

F. Microcontroller

A low-power 8-bit microcontroller (ATXMEGA64) with 12-bit ADC was used to digitize the signal and perform minimal processing.

G. Automatic Gain and Offset Adjustment

Since the 3V rails on the sensor do not provide much dynamic range, it was very important to be able to scale the input signal appropriately in order to maximize the dynamic range of the 12-bit ADC. Since the ATXMEGA also contains a 12-bit DAC, this voltage output was used as the negative input to an instrumentation amplifier. In addition to adjusting the gain, this provided a means to automatically subtract the DC offset, which is often a problem in microwave Doppler designs.

H. Wireless Link

A commercial 2.48 GHz radio link (TagSense ZT-Link) was used to relay the data wirelessly to nearby radio base station. The data transport protocol is based on IEEE 802.15.4 physical layer protocol compatible with low-power operations and ad-hoc wireless sensor networks.

I. Battery and Power Consumption

The power consumption of the microwave unit was less than 30 mA when operating. For certain applications, the average power can be reduced significantly by using low-duty cycle operation and only taking measurements at periodic intervals. For short-term use, the unit was powered by two 2530 coin cell batteries. These could be replaced by a flat rechargeable lithium cell for long-term use.

The total parts cost of the Doppler radar unit was approximately US\$25, which includes the price of the printed circuit board, but does not include the cost of the radio data link (~US\$35.).

IV. EXPERIMENTAL TESTING AND RESULTS

Several tests were performed to better understand the signal morphology and test reproducibility.

A. Comparison with ECG

For the purpose of validation, data was collected simultaneously from the wearable microwave sensor as well as a Bluetooth-enabled portable commercial ECG unit (Alive Technologies) [20]. Sample results for one person are shown in Figure 4.

Fig. 4. (top) typical raw signal from microwave sensor. (bottom) data trace from portable ECG device collected simultaneously.

A comparison between ECG and microwave Doppler at 1 meter distance has been published [21]; however, the signal from the wearable microwave sensor presented here contains much more detail due to the much shorter distance.

As shown in the data, the rising edges of the microwave waveform coincides with the R-peaks in ECG. However, since the microwave sensor directly measures motion and not the electrical activity of the heart, the morphology is not expected to be the same. The microwave scan waveform contains additional fine structure, indicating secondary movement, presumably in different regions of the heart. An additional low-frequency modulation in the baseline is due to breathing, but this slow modulation is not evident at the shorter time scales displayed here in Figure 4.

B. Patient Data Variability

In order to investigate the reproducibility of the microwave sensor across multiple people, a second experiment was conducted to compare multiple scans from five people. Between measurements, the microwave sensor was removed and remounted in approximately the same location for each person through the clothing. Sample data from three of the participants is shown in Figure 5.

As expected the data from multiple scans of the same patient were quite similar. However, the substructure in the scans from different patients show significant differences in the substructure, perhaps due to differences in individual heart position as well as individual heart mechanics.

Fig. 5. Sample microwave scans taken from three different people (left, middle, right). Horizontal scale is 500ms/division, vertical scale is 0.5V. The top row of scans were taken with horizontal polarization and the bottom row of scans correspond to vertical polarization. The rightmost data was collected from a person with medically diagnosed Wolf-Parkinson-White syndrome.

C. Effect of Polarization

Since the microwave antenna used in the sensor is linearly polarized, it was also of interest to test the effect of polarization. The microwave scans were consecutively collected from each participant using vertical and horizontal polarization, respectively. This was accomplished by simply rotating the wearable sensor 90-degrees in between scans and re-clipping it to the person's shirt. In both cases, the sensor was attached to the person's chest, just above the base of the sternum. These results are also shown in Figure 5. It is interesting to note that the scan using horizontal polarization seemed to produce greater detail in all cases.

VI. CONCLUSIONS AND DISCUSSION

We have presented a new category of wearable sensor for ambulatory cardiac monitoring based on a near-field version of microwave Doppler radar. The small size, low power, and ability to operate through clothing makes this device well-suited for use in mobile health applications. The sensor can be easily clipped to existing clothing or embedded in special garments such as a vest or even a blanket.

Unlike long-distance Doppler radar detection, the morphology of the waveform obtained from the near-field microwave sensor includes a significant amount of

features that may also be of clinical use. The microwave Doppler sensor is not a direct substitute for ECG, since the electrical activity of the heart is not measured by microwave Doppler. However, it may be an interesting portable and lower cost alternative to M-mode echocardiography for monitoring of certain types of heart failure associated with heart mechanics, such as depressed systolic function (e.g. depressed ejection fraction), akinesia, and fibrillation.

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