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Low-Cost Differential Front-End for Doppler Radar Vital Sign Monitoring

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Abstract — **We present a differential front end design for improving the performance of short-range low-cost Doppler radars for vital sign detection with application to automotive driver safety systems, health monitoring, and security screening. By using dual helical antennas each with a 40-degree beamwidth, it is possible to illuminate the body in two adjacent locations to perform a differential measurement. Since only one of the beams illuminates the heart, the baseband signal from the second radar is used for motion cancellation. We demonstrate this approach using a custom-designed dual helical antenna and simple direct-conversion radar circuits implemented in microstrip operating at 2.460 GHz and 2.510 GHz., respectively. Heart rate data is shown for detection distances of 0.5 meter showing reduction in background motion noise compared to data from traditional single radar unit design.**

Index Terms — **vital sign, biomedical signal detection, heart rate, Doppler radar, differential, helical antenna.**

I. INTRODUCTION AND MOTIVATION

Over the past decade, there has been an increasing interest and need for creating wireless health monitoring systems. In addition to a variety of wireless health and medical devices, there is a strong preference to using non-contact technologies to monitor vital signs [1-3].

Long-range detection systems are often discussed for applications such as Search and Rescue operations, field hospital systems and assisted living facilities.

In should be noted, however, that there are several emerging applications for *short-range* vital sign monitoring as well. These include:

1) Automotive safety systems – there is an interest to detect the heart rate of commercial truck drivers, for example, and detect erratic heart rate which can be caused by use of drugs or lack of sleep.

2) Kiosks and Automatic Teller Machines – there is an interest in screening unusual heart activity in certain security checkpoints, airport ticket kiosks, and bank teller machines.

3) Airports/Casinos – for certain security screening systems, there is also interest in detecting unusual physiological activity.

In order to make possible commercial applications of this technology, several key problems need to be overcome, including device cost and noise due to motion.

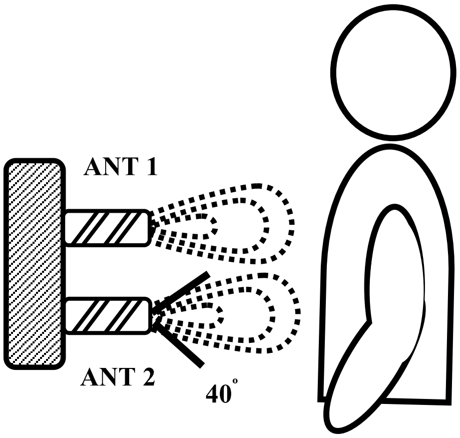

Fig. 1. Illustration of dual antenna Doppler radar design for vital sign monitoring. The beam from upper antenna illuminates the heart, while the beam from lower unit is used for motion compensation.

II. VITAL SIGN MEASUREMENT

The field of wireless vital sign monitoring has a relatively long history, almost as long as radar itself [4-6]. Doppler radar has been the primary means of performing vital sign monitoring by using the backscatter signal from a beating heart [7-9]. Over the past 20 years, the advent of integrated chipsets, MMICs, microstrip circuits, miniature antennas, and better substrate materials have all contributed to large improvements in the cost and performance of small low-power radar units for many different applications. As an example, we can currently find small inexpensive 26 GHz radar modules used in motion sensors and automatic door opener systems in retail stores.

More recently, the increasing computing power of embedded computers and small microcontrollers is now making possible the ability to implement significant computational algorithms to analyze, filter, and clean the data from such small radar systems [12-13]. It has been shown that high transmit power is not necessary to achieve good results with Doppler radar [10], and other detection methods, such as Ultra-Wide Band sensing, are also being explored.

Despite these advances, the significant problems that remain are finding better ways to reduce background motion noise in such systems while maintaining very low-cost [12].

In this paper, we consider antenna diversity and explore the use of a simple dual-antenna system for achieving improved performance in short range low-cost Doppler radar vital sign monitoring.

III. System Design

The goal of our research is to create a radar front end that automatically compensates for background motion before any digital signal processing is done. As a first step to testing this concept, we chose a dual radar design shown in Figure 1.

As shown in the figure, the top radar unit (labelled "Antenna 1") illuminates the heart, and the second lower radar unit does not. Although it is certainly possible to combine the signal from each antenna build a measurement matrix [12], we decided to explore how the two radar signals could be combined in baseband to achieve motion cancellation.

The choice to operate each radar independently is made possible by several key factors:

1) Multi-frequency operation – each radar is relatively narrowband and the ISM band (~2.4 GHz) is sufficiently wide that each radar could be operated at a separate frequency.

2) Signal polarization – the design of our antennas enables us to cross-polarize the signal as necessary to further isolate each radar signal.

3) Modularity – self-contained low-cost radar units are now commercially available and provide a means to easily scale this design to higher frequencies and more radars.

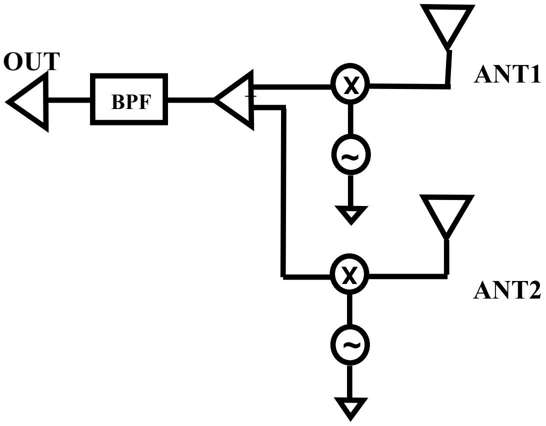

Fig. 2. Simplified block diagram of dual radar design, operating at 2.46 GHz and 2.51 GHz respectively.

IV. Circuit design

A. Antenna design

In order to achieve a narrow beamwidth, a helical antenna design was chosen [14]. Antennas we constructed by winding copper tape on a low-loss acrylic tube. The circumference of the tube was chosen to match the wavelength and the length of the tube (determined by the number of turns) was chosen to meet our desired beamwidth requirements. The pitch of the windings was experimentally determined by optimizing the antenna gain and specified by the turn spacing S, such that pitch = $\arctan(S/\pi D)$ Both left-handed and right-handed polarization versions were made.

Antennas were testing and optimized using an Agilent 8753D vector network analyzer. The following are the final parameters of the antennas used in the Doppler radar system:

$f = 2.45\text{-}2.5$ GHz
$\lambda = 12.2$ cm.
$C = 1.14\lambda$
$N = 4$ turns
$S = 0.27\lambda$
$Z = 160\Omega$
Half-Power Beamwidth= 42°

B. Oscillator and Mixer

Each radar unit was implemented using a common-base oscillator and diode mixer which producing a baseband output (Figure 2). (quadrature can be achieved using a second mixer diode 90-degrees apart) The oscillator was stabilized and tuned using a microstrip line resonator. The entire circuit was implemented on Rogers 4350 copper laminate substrate in order to achieve higher Q-factor and better phase noise in the microstrip resonator.

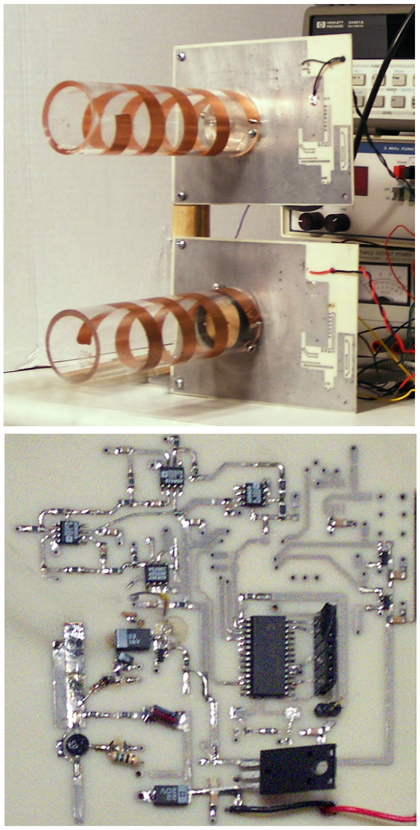

Fig. 3. (top) front side of radar units showing antennas. (bottom) back side of single radar unit showing circuit.

C. Baseband Filter

The outputs of the two radar units were fed to an instrumentation amplifier to perform baseline subtraction before feeding to the main filter stage.

Although little RF power is needed for this application, we chose to use a 12-volt power rail for the receive section in order to maintain the large dynamic range necessary for filtering and analog processing. Despite the relatively high voltage rail, op-amp active filters were used for the baseband filtering to save power and size.

In addition to scaling and offset adjustments, the main baseband filter section consisted of two 6-pole elliptic filter sections with zeros at 60 Hz and corner frequencies of 100 Hz and 80 Hz respectively. By using an elliptic filter design, good signal to noise ratio was achieved using a minimum number of op-amps and board space.

The completed front end system is shown in Figure 3. It should be noted that the parts cost of the entire system was less than US$25.

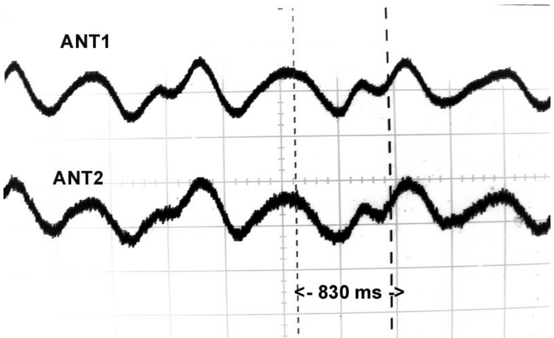

Fig. 4. Sample outputs from both individual radar units while moving an object in front of antenna.

IV. RESULTS AND DISCUSSION

In order to test the effectiveness of the dual-radar design, we first measured the individual outputs of both radar units side by side. As shown in figure 4, the output of the two radar units tracked fairly well.

The output of the entire dual-radar front end was then tested using human subjects and measuring the output on an Agilent Digital storage oscilloscope. A sample measured waveform is shown in Figure 5. Heart rate was verified using both a commercial pulse oximeter and manual pulse measurement. Most interestingly, the heart waveform shows clear structure, with R-waves visible, which suggests that such data can also be used for diagnostic purposes in addition to simple heart rate measurement.

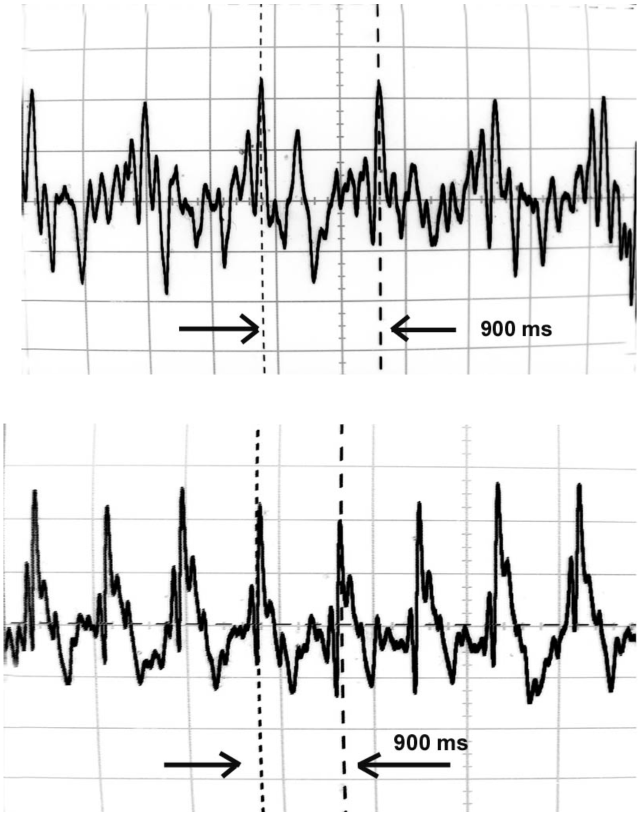

Fig. 5. (top) Heartbeat signal from a single radar unit with no motion compensation. (bottom) Heartbeat signal from dual-radar unit showing reduced background motion noise. Data taken at 0.5m.

As shown in Figure 5, the dual-radar design shows clear improvement over a single radar operating alone. While this approach is effective in mitigating "common-mode" background artifacts, it was quickly discovered (Figure 6) that "differential-mode" motion due to breathing cannot be so easily compensated (but can be post processed). Since the motion of the chest and diaphragm are not equivalent within the beam spot zone of each radar, the two signals cannot be entirely subtracted. In addition, it is important to note that since the two radar units are operating at slightly different frequencies (with different rates of phase advance), the relative phase shift as a function of motion is slightly different. Nevertheless, the differential subtraction utilized in this approach provides significant improvements overcoming general motion noise and, most importantly, this design enables further post processing of the data by effectively reducing the dynamic range and clipping of the signal caused by large motion artifacts.

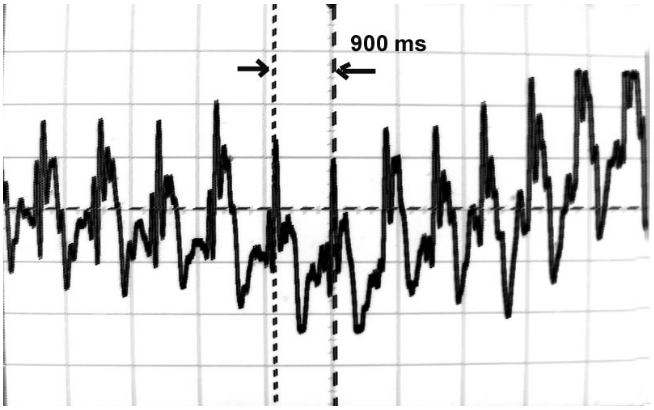

Fig. 6. Sample data from dual antenna unit at 0.5m showing effect of respiration.

VI. CONCLUSIONS

A dual-antenna Doppler radar system for vital sign monitoring has been developed and demonstrated with improved performance and reduction in background motion noise. The front-end design is adequate for short range applications (1 meter) but can be extended further with signal processing [13].

The use of multiple antennas provides an interesting domain for future work, including further exploration of antenna polarization and directivity.

In addition, the design presented here demonstrates low-cost design and feasibility of practical commercial use of short-range, low-cost vital sign monitoring in a variety of applications including health, safety, and security.

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