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Self-Powered 24-GHz Doppler Radar for Building Entrance Monitoring Using Cross Correlation and Envelope Detection

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***Abstract* — A 24-GHz Doppler radar self-powered by solar energy was designed, fabricated and tested for building entrance monitoring. The implemented RF board includes two 4×4 patch arrays, a voltage-controlled oscillator, two low noise amplifiers, and a six-port structure. The solar energy harvesting system has a fractional open-circuit voltage maximum power point tracking circuit, a boost charger controller, two 90mm×5mm×3mm (L×W×D) 200 mW solar panels, and a main and backup battery. Moreover, a cross-correlation method to detect activity in the radar range and a novel envelope detection method to determine the target walking direction were developed and tested. The radar system is featured as being flexible and portable. The complete radar system has dimensions of 118mm×45mm×20mm.**

***Index Terms* — energy harvesting, Doppler radar, human detection, MPPT, cross-correlation, envelope detection.**

I. INTRODUCTION

The increasing interest for the internet of things (IoT) has raised the demand on low-power smart sensors which can be easily placed even at difficult access locations for long periods of operation without the need to replace the batteries or with near-perpetual operation using renewable energies such as solar, wind, geothermal etc. Among these renewable energy options, solar may be the most promising since it provides higher power densities and is becoming a solution in remote sensing applications where the sensors are deployed in large quantities (e.g. environment monitoring and infrastructure surveillance) [1].

Among various types of sensors, radar systems are now being widely studied. A lot of technical publications have been found in the literature with applications such as human tracking, vital signs detection, gesture recognition and activity monitoring [2]. Nevertheless, no publication was found by the authors on radar systems including energy harvesting system as their main power source to facilitate their massive deployment and inclusion in the IoT wireless sensors networks.

In this work, a self-powered 24-GHz radar for building entrance monitoring is proposed. The six-port radar architecture reported in [2] was adopted with some changes in the baseband to reduce its power consumption. The baseband board has low-frequency amplifiers and up-converting mixers to allow the use of an audio card to sample the baseband board. The power management system consists of a fractional open-circuit voltage maximum power point tracking (MPPT) circuit, a lithium-ion rechargeable battery, two 90mm × 25mm × 3mm (L×W×D) 200 mW solar panels, a boost switching voltage regulator, a boost charger controller, and a backup battery that avoids the system from turning off in poor sunlight conditions. To reduce the radar power consumption, the system goes to sleep mode 10 times per second, reducing the average power consumption to 50 mW, which can be sustained by the solar energy harvesting system. Moreover, a cross-correlation method to detect activity in the radar range and an envelope detection method to determine the target's walking direction are proposed.

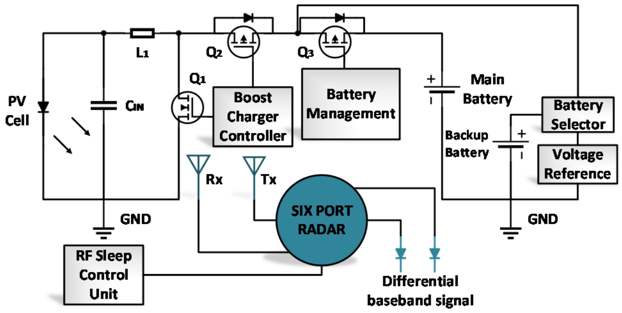

Fig. 1. Solar energy harvesting system and six-ports radar block diagrams.

The rest of the paper is organized as follows. Section II details the design principles of the system and the signal processing methods. In Section III the results of the experiments are shown demonstrating the system's capability to detect activities and walking directions. Finally, a conclusion is drawn in Section IV.

II. DESIGN PRINCIPLE AND SIGNAL PROCESSING

Fig. 1 shows the schematic of the implemented 24-GHz radar system. Two Schottky diodes are connected at the differential baseband ports as part of a six-port architecture, with patch array antennas for transmitting (TX) and receiving (RX) RF signals. The overall radar power consumption is 50 mW, which is achieved by turning off and back on the radar 10 times per second using the sleep control unit switching signal.

A. Power Management Circuit

The MPPT circuit is implemented to maximize the power generated by the photovoltaic (PV) cell. The boost charger controller (Fig. 1) switching signal modulates the Boost DC/DC converter's (consists of C_{IN}, L1, and transistor Q_1) input impedance, which indirectly modulates the PV cell output voltage to reach the maximum power transfer point

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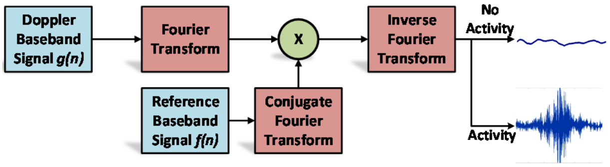

Fig. 2. Block Diagram of cross-correlation signal processing.

at typically 70-80% of the PV cell open circuit voltage (Voc) [3]. Taking advantage of this, the implemented system senses the Voc every 16 seconds by disconnecting the PV cell from the boost charge controller for 256 ms, setting the PV cell regulation to 80%. The system has a low-power voltage reference, which through a high resistive voltage divider sets the maximum and minimum voltages (4.2V-2.4V) for the main lithium-ion battery to maximize its life span. The voltage reference also serves as the reference for the main battery to back up the battery commutation system. The TI BQ25505RGRR IC was used for the MPPT and the boost charger controller.

As the main battery output ranges from 2.4 V to 4 V, a boost switching voltage regulator is needed to keep the radar supply voltage between its operation range (5.5 V to 4.5 V) regardless of the battery voltage. For this purpose, the TI TPS610997YFFR IC was used, offering up to 93% efficiency and ultra-low power consumption.

B. Signal Processing Procedure

A review of other methods of human activity monitoring have shown successful results but have limitations in adaptability due to several reasons. Some methods require the use of a threshold of signal strength [4], then are highly dependent on human intervention and are prone to false positives in detection. Additionally, an *I/Q* receiver architecture is usually needed to determine the moving amplitude or direction which increases complexity [5]. In this work, instead of using an *I/Q* architecture, a single-channel approach is adopted to accurately detect the movement direction based on a combination of envelope detection and cross correlation. After envelope detection determines that the incoming signal matches a target walking in or out, this signal is used to perform a cross correlation to confirm the direction after removing the noise.

For a person entering a building, the amplitude of the signal is expected to have a slowly increasing exponential behavior as the target approaches the radar. As soon as the target crosses the door, the amplitude will decay rapidly in the form of another exponential curve. This is the key to determine the direction of a target movement. A direct spectral analysis is not enough to reject some noise present in the doorway. For this purpose, envelope detection is performed to filter out the high-frequency components of the signal with the RMS value of a select number of samples. In other words, the envelope is calculated by squaring the Doppler baseband signal and sending it through a lowpass filter. Squaring the signal effectively removes its sinusoidal component by using itself as its carrier wave, leaving as a result just the Doppler baseband signal amplitude variation due to the subject displacement toward or away from the radar. Therefore, half of the signal energy is pushed up to higher frequencies and the other half is shifted down to DC. Then a lowpass filter is used to eliminate the high-frequency component. The squaring process is carried out in (1), where n is the window size. Moreover, the summation of the squared values is also performed to get the effective output, this operation is continuously carried out to the radar-detected signal based on a time-domain sliding window.

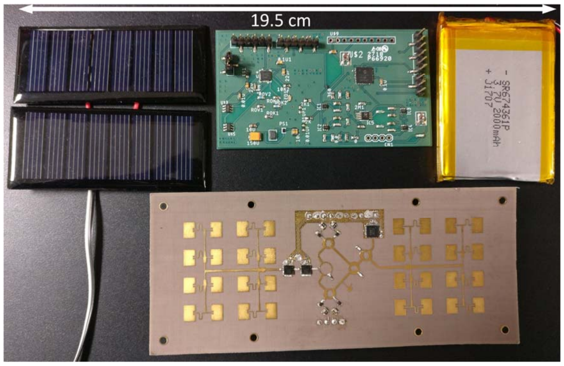

Fig. 3. Radar System building blocks.

$$RMS\{x[i]\} = \sqrt{\frac{1}{n}\sum_{j=i-n+1}^{i} x^2[j]} \quad \forall \quad n \leq i \qquad (1)$$

Additionally, to make sure that the direction of movement was accurately predicted, a cross correlation is performed to identify a match of the Doppler baseband signal with the reference baseband signal. Since the signals of a target walking in and a target walking out are inverted in shape, the system takes advantage of this distinction. If a reference baseband signal of a target walking in is pre-selected, a high correlation at zero lag is expected. For a target walking out, a cross correlation calculation using the same pre-selected image will yield high correlation at both sides of the maximum lag instead. This is because one image is the mirror of the other. This processing is performed by applying the following to the obtained baseband signal:

$$(f * g)[n] \overset{\text{def}}{=} \sum_{m=-\infty}^{\infty} f^*[m]g[m+n] = \mathcal{F}\{f\}^* \cdot \mathcal{F}\{g\} \qquad (2)$$

where f is reference signal, g is the Doppler baseband signal, and $\mathcal{F}$ represents the Fourier transform.

Moreover, to reduce the computational cost of applying (2) to a large window, the baseband signals fast Fourier

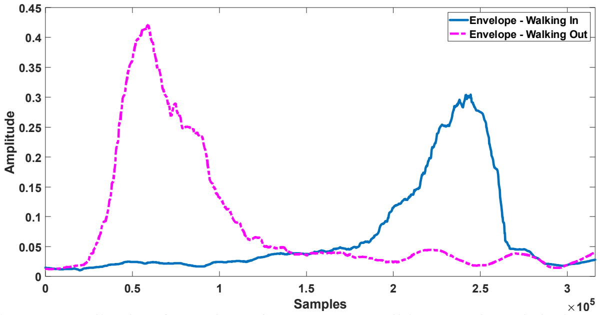

Fig. 4. Amplitude of envelope for a target Walking In (dotted dash) and Walking Out (continuous).

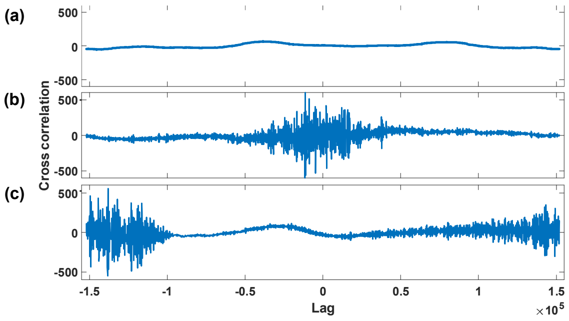

Fig. 5. Cross correlation plots showing “NOTHING” (a), “IN” (b) and “OUT” (c) being correlated with a reference signal “IN”.

transform (FFT) was used for the cross-correlation calculation since the use of FFTs give better results than direct approaches for large enough windows [6]. With these considerations, the block diagram for the signal processing procedure is shown in Fig. 2.

Since the envelope detection can also provide a smoothing filter to the response’s maximum amplitude, this makes extraction of data easier for future work where pattern recognition techniques will be applied.

III. EXPERIMENT AND RESULT ANALYSIS

The radar system used for the experiments consists of a signal processing/power management board, a lithium-ion battery, a six-port 24 GHz Doppler radar, and two 200 mW solar panels, as shown in Fig. 3. The Doppler radar takes data facing out of a building pointing from the front of a doorway and the baseband signal is sampled at 20kHz. The test environment considers a person crossing a doorway in both directions. This analysis will refer to a target walking in as “IN”, a target walking out as “OUT” and no target as “NOTHING”.

This signal is processed with an envelope detection to determine the direction of movement and choose the reference baseband signal. Results are shown in Fig. 4 for a person walking in and walking out respectively. This signature shows the shape in the amplitude increase by ignoring the Doppler components themselves and determines the direction by the rate of change in the envelope directly. By verifying that the amplitude of the envelope of the Doppler baseband signal crosses over a threshold while it goes up and crosses it again while it drops, the information is recorded on a window that is reconstructed to be fed into the system for comparison.

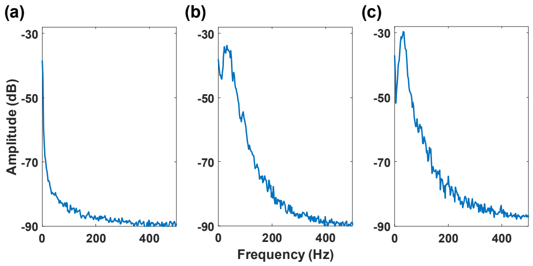

Fig. 6. Welch method PSD outputs for “NOTHING” (a), “IN” (b) and “OUT” (c).

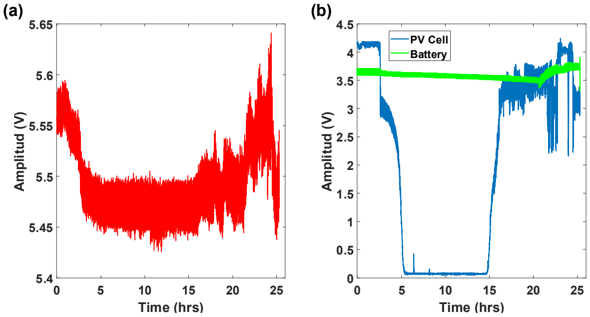

Fig. 7. Regulator voltage output (a) and PV cell/battery voltage output (b) for 25 hours.

With this reconstructed data, a cross correlation analysis is performed by comparing the Doppler baseband signal with the reference baseband signal. Based on these results, the reference is pre-selected from two possible outcomes. By performing a correlation of the Doppler baseband signal with references “IN” and “OUT”, the direction of movement can be confirmed while avoiding false positives during detection.

A high correlation shown in zero lag when comparing with reference baseband signal “IN” represents a match. Because the shape of the signal “OUT” is similar to “IN” but opposite in direction, the cross correlation of this plot is expected to have high correlation at the maximum lag. This is proven in Fig. 5, while also confirming that there is no correlation between the reference baseband signals “IN” or “OUT” and the Doppler baseband signal “NOTHING”.

Spectral analysis of this signal is then used to determine the Doppler components. The Welch method is used for power spectral density estimation, with an FFT size of 8196 points and a signal overlap of 50% of each window. The window selected is a Kaiser window with beta of 4. This allows a more accurate peak detection as shown in Fig. 6.

Finally, the solar energy harvesting system was tested for 25 hours to evaluate its capacity to supply the radar system. The results are shown in Fig. 7, where the night time occurred between the hours 5 to 15. As expected, during the night time the battery voltage decreased, the PV cell voltage stayed close to 0V, and the boost switching voltage regulator output went slightly down. When the sun came up, the PV cell voltage increased supplying enough power to charge the battery and supply the radar system.

IV. CONCLUSION

A portable 24-GHz solar self-powered radar was designed, implemented, and tested. A cross-correlation activity monitoring method and a novel envelope detection-based target walking direction determination algorithm were proposed and tested. Experiments with different people walking toward and away the building were carried out. To the best of the authors' knowledge, there is no other self-powered radar previously reported in the state of the art, nor an envelope walking direction detection method using a single-channel Doppler radar.

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