Millimeter Wave Six-port Radar Sensor for Precise Displacement Measurements and Gesture Sensing Applications

Salam Benchikh, Homa Arab, Emilia Moldovan, Serioja Ovidiu Tatu

INRS-EMT, 800 de la Gauchetière Ouest, Montréal, Québec, Canada, H5A1K6

Abstract — **This paper presents a millimeter wave bistatic radar sensor for short-range applications. The sensor can detect the precise movements of subjects and to estimate the distance and relative velocity. A six-port architecture is used. The sensor operates at 79 GHz and generates differential quadrature baseband signals that can be directly used, without complex signal processing, for different measurement applications. A calibrated tuning fork experiment validates precise displacement claim by measuring the mechanical oscillation frequency. Several hand gesture experiments are also performed with promising results. The proposed simple, robust and low-cost radar sensor can be used in industry, biomedical domain and security.**

Index Terms — **Antenna-in-package, hand gesture recognition, millimeter wave technology circuits, motion detection, passive radar, sensor systems, six-port.**

I. Introduction

Originally, human hand gesture recognition was a topic in the area of computer science, which used cameras and computer vision algorithms for interpreting human hand gestures [1]. Most gesture sensors are of contact type. However, contactless concepts are more favored because they allow for more freedom in daily life, such as inertia sensors in the Wii system [2], Xbox Kinect based on three-dimensional video analysis etc. Those devices have important power consumption and are affected by ambient light conditions. In addition, the device cannot detect through obstacles. Microwave radars could solve this problem as they consume much less power and can detect through obstacles. Four decades ago, the area of microwave started to be attracted by human gesture recognition based on radar technologies [3]-[4]. Performance improvements in radar techniques in the last decade have led researchers towards the application of radar sensors in various other fields. Recently, millimeter wave radars for hand gesture sensing have captured the attention of researchers. In [5], Authors have used BGT60TR24 chipset from Infineon to design their radar. They focused on complex signal processing and simple hardware design, using the Frequency Modulated Continuous Wave (FMCW) technology. It operates in V-band with a central frequency of 60 GHz. In [6], the system is dedicated to intelligent driver assistance systems and works in a 25 GHz K-band. it is based on an Infineon BGT24MTR12 chip. Also this system is based on complex signal processing and simple hardware design. [7] shows retransmitted wireless communication signals for Doppler radars. This sensor is based on an injection-locked quadrature receiver architecture. It operates in S-band with a central frequency of 2.4 GHz. A coupler and an injection-locked oscillator were the only components made by the authors.

Millimeter wave frequencies are still not widely used in industrial applications despite their very high measurement accuracy because of important technical challenges.

In this paper, we describe a novel millimeter wave non-contact sensor radar system. The system architecture is based on six-port technology and requires low complexity signal processing. The active part of the radar sensor is reduced to a Continues Wave (CW) oscillator. Also, since six-port determines the phase-shift and the magnitude of reflation coefficient, the mathematical treatment and the acquisition of measured data became easier [8], [9].

II. Operating Principle

A. Problem Description

The radar system design comprises the hardware part and the digital signal processing part. A variety of design choices exist for each subsystem according to the application specifications. The transmitter hardware is designed to generate the specific transmitted waveform function of measurement needs. In addition, the transmitter is characterized by its carrier frequency and bandwidth. In the microwave regime, radar systems operate over a wide range of frequencies, from 300 MHz to 300 GHz. A radio license is required to operate a microwave device in most of the electromagnetic spectrum. Exception is made for industrial, scientific and medical (ISM) bands, and allowed frequencies for specific applications (such as radar sensing from 76 to 81 GHz) where licenses are not required. The operating frequency of our sensor is chosen in ISM bands. In classic radar receivers, a mixer is used to extract the useful information from the received signal [10]. A mixer is a non-linear device that requires a relatively high LO power or DC bias. To reduce power consumption and cost, we propose a six-port radar architecture.

B. Six-port Radar Sensor

The bloc diagram of the proposed sensor system is shown in Fig. 1. The RF signal generator transmits a CW signal to the target through a branch coupler and a Tx antenna array. The target reflects a part of the transmitted signal to the Rx antenna array. The six-port receiver is based on the interferometric principle, and the received signal and the reference transmitted signal are combined under four different relative phase shifts to produce four outputs [11].

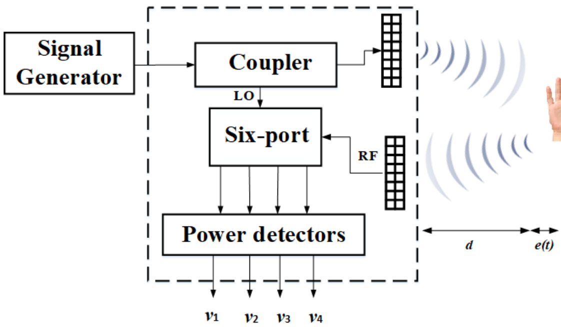

Fig.1: Bloc diagram of radar sensor.

Down-conversion to baseband is achieved by using power detectors connected to six-port circuit outputs. The in-phase and the quadrature signals, with a relative phase shift of 90° in between, are given as follows:

$$i(t) = v_1(t) - v_3(t) \quad (1)$$

$$q(t) = v_2(t) - v_4(t) \quad (2)$$

where *i(t)* and *q(t)* are the in-phase and quadrature signals, respectively. The v_i are the output voltages of the power detectors. To ensure that one channel is not in the null detection point, we use the quadrature receiver [3]. The complex signal demodulation is expressed as:

$$b(t) = i(t) + jq(t) \quad (3)$$

The argument of *b(t),* is the phase/frequency shift between input signals. Details on frequency, phase, and amplitude discrimination can be found in [9], [10].

C. *Hardware Implementation*

As seen in the right top corner of Fig. 2, the short-range sensor was integrated in the Miniature Hybrid Microwave Integrated Circuit (MHMIC) technology and mounted in a metallic fixture for laboratory measurement purposes. The substrate is a 127-μm thick alumina having a relative permittivity of 9.9. The mm-wave six-port interferometer is a passive circuit, a combination of four 90^0 hybrid couplers interconnected by transmission lines and a 90^0 phase shifter. Quadrature differential baseband signals are obtained using four highly sensitive power detectors. Each one is implemented with a 90° hybrid coupler and a pair of HSCH-9161 Schottky diodes, to insure a minimum return loss over a wide frequency band of more than a 10 GHz. Therefore, the whole circuit uses eight identical couplers and eight Schottky diodes in a symmetrical architecture. To reduce the size of the prototype, the antenna arrays (8x2 patch antennas, 14 dBi gain) are integrated on the same ceramic die.

The radar sensor operating frequency covers the former 76-77 GHz and the newly allocated in Europe 77-81 GHz bands. The laboratory short-range measurements are done at 79 GHz.

III. Experimental Results

Measurement set-up includes the Anritsu 68347C microwave signal generator, the millimeter wave active multiplier from OML (X6), and the Tektronix DPO7054 digital phosphor oscilloscope, as seen in Fig. 2. The output power generated by OML multiplier is max 7 dBm. Considering the WR12 to microstrip transition loss we estimate at 5 dBm the power before the TX antenna array, and at -7 dBm to LO signal power, much lower than for conventional diode mixers.

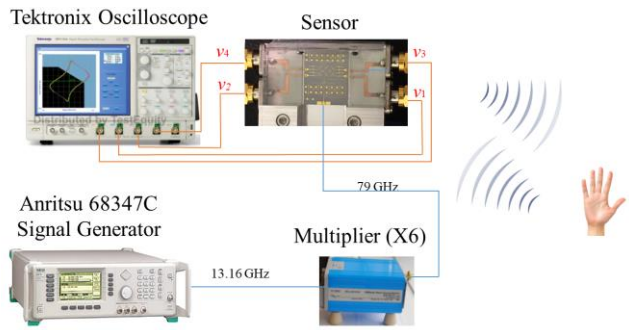

Fig.2: Short distance measurement set-up.

The evaluation of the reliability of the proposed technique has been performed by two experimental setups.

In the first one, investigations on tuning fork kit have been carried out to validate the mechanical oscillation frequency measurement. The tuning fork kit frequencies start from 100 Hz and end at 4096 Hz. The target is placed in front of the radar sensor. Several tuning forks with different frequencies are performed at a distance of 20 cm from the sensor. Fig.3 a) shows the in-phase received signal while striking the two branches of a 100 Hz tuning fork resonator in front of the Tx/Rx antennas. For convenience, Matlab software is used to receive and analyze the data collected by the oscilloscope from the measurement set-up and in-phase signal is shown in this article and not quadrature signal. Both in-phase and quadrature signals contain the tuning fork frequency information. By analyzing the in-phase signal of a 100 Hz tone and by using Fast Fourier Transform (FFT), we get that the measured in-phase signal frequency is equal with the audio frequency marked on the fork as seen in Fig.3 b). Because the fork was held in hand, its light movement generated distortion on the sinusoidal waveform, without affecting the frequency measurements. The measured I/Q frequency is equal with the audio frequency marked on the fork (100 Hz - 4096 Hz) within 1Hz accuracy.

In the second setup, the aluminum plate and hand gestures targets are performed in front of the radar sensor. An aluminum plate with cross section of 0.01 m^2 is moved back the sensor over 20 cm displacement range. Complex representation of the received signals is shown in Figs.3 c).

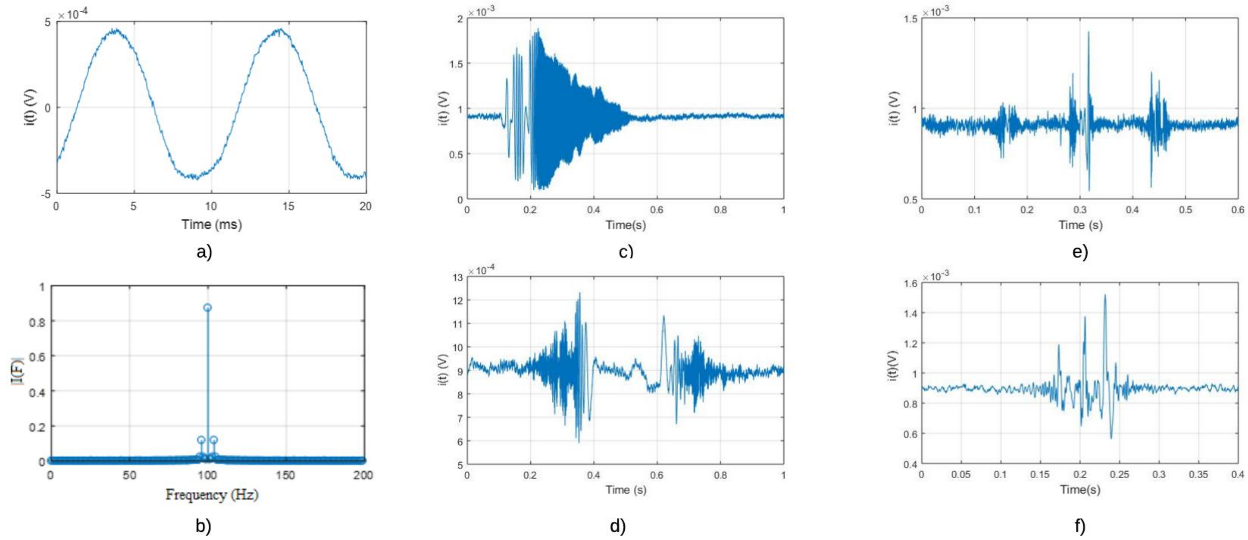

Fig.3: a) 100Hz tuning fork received signal, b) FFT of 100Hz tuning fork received signal, c) Metallic rectangle facing antennas and moving back, d) Received signal of hand movement front and back, e) Counting one, two, and three fingers f) Counting three fingers.

The magnitude of the signal is decreasing. The palm of hand is open and facing the radar antennas, while moving front and back is performed in Fig.3 d). The envelope of the signals is theoretical symmetrically versus the vertical axis. The difference between the front and back signals is due to the irregular trajectory and velocity of the hand movement. Since the target is aluminum, the amplitude of the received signal is higher in Fig.3 c) as compared to Fig.3 d). Furthermore, the experiment deals with hand fingers counting. Fig.3 e) displays one, two, and three fingers with different magnitude facing the radar sensor successively at 20 cm. For each finger facing the sensor, we have a shape of hand movement front and back presented in Fig.3 d). As explained in the previous paragraph, the difference between the shape of each finger is due to the irregular trajectory and velocity of the fingers movements. Fig.3 f) displays three pics corresponding to three fingers with different magnitude facing the sensor at a distance of 20 cm. Therefore, without using any algorithm or signal processing, we can easily count the number of fingers facing the sensor.

IV. Conclusion

Research on a novel interferometric millimeter wave radar sensor is presented. The described prototype was developed for precise distance and velocity measurements and detecting of human hand gestures required in human to machine interfaces. The distance between the target and the radar sensor, operating at 79 GHz with 5 dBm transmitted power, is around 20 cm. A tuning fork experiment using a CW signal is performed to prove the frequency measurement accuracy of mechanical vibration, 1Hz. The range and speed can also be measured with high resolution if a FMCW signal is used instead of a CW one. The hand reflected radio signals are correlated with gestures in front of the received antennas. In our opinion, the proposed simple, robust, and low-cost radar sensor is well suited for various industrial, biomedical and security applications.

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