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A low cost non-imaging system for standoff threat detection

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Abstract— We introduce a narrowband polarimetric FMCW radar for concealed threat detection from standoff distances. The working frequency is 24GHz and this system enables the threat detection from distances up to 15 meters. After showing that cross polarization discrimination of the torso of a typical human is better than 20 dB for vertical polarization, we utilize the cross polarization response of the target for distinguishing between a threatening and non-threatening target. Concealed threats increase the cross polarization reflection of the torso by more than 10dB. All antennas in the system provide at least 30dB cross polarization ratio. The integration time can vary between 0.2 and 2 seconds. Increasing the scan time significantly improves the performance of the radar. This system proposes a detection probability of more than 80% and false alarm rate less than 5% for integration time of one second.

Index Terms— Polarimetric radar, FMCW radar, reflector antenna, dual-mode horn antenna, cross polarization discrimination

I. INTRODUCTION

Over the past years, terrorist attacks have inflicted heavy human casualties. In person born attacks, the suicide belt is concealed under normal clothing, giving the threat a great deal of room for maneuvers like running or moving in all directions. This capability makes the PBIEs the most fearing threats due to its potential for increasing the human casualties. A solution to this problem is monitoring people at standoff distances.

Wide range of frequency bands from UHF to X-ray are utilized for imaging or detection of concealed threats. Different types of clothing are transparent to X-ray beams and X-ray imaging systems offers excellent imaging resolution. Unfortunately, due to the ionization and health risks of X-Ray imaging systems, they are not acceptable for practical scenarios [1].

References [2-3] has shown that normal clothing is highly transparent to frequencies less than 600 GHz. Therefore, millimeter-wave and THz frequencies are promising candidates for security imaging applications.

A portal diffraction-limited active imaging system is developed in [4-6]. This system operates at 27-33 GHz frequency band with a scan time less than 10 seconds. By changing the mechanical scanning from linear to cylindrical, [7-8] has revised this system to a video frame rate 3D imaging system.

In [9] a novel multistatic millimeter-wave portal scanning system with a elliptical toroidal antenna in 57-64GHz is presented. This system reduces the 3D reconstruction problem to a 2D system, thus reducing the computational complexity considerably.

Several passive imaging systems are developed for portal scenarios, as well [10-11]. The differences in emissivity and reflectivity of body and objects hidden beneath clothing is the meaus sure for resolving the concealed object. These systems work efficiently in outdoor scenarios.

Aforementioned systems work in portal scenarios and are not applicable to standoff cases. Indeed, the cross range resolution of the system is restricted by the physical size of the transmitter antenna. Thus, for standoff imaging at distances up to 20 meters, the transmitter antenna size increases significantly, limiting the speed and accuracy of the system.

Several THz imaging systems are proposed [12-15]. In [13-14] three single pixel systems at 300GHz and 645GHz with a rotational scanning mechanism is introduced. Reference [15] has demonstrated several multi-pixel systems working at 812GHz. Unfortunately, none of these designs enables standoff imaging from distances more than 10 meters.

A single pixel 675GHz imaging system with 1Hz frame rate is developed at the Jet Propulsion Laboratory [16-19]. This system can distinguish between a weapon, a belt and other threats with effective range of 25 meters, cross range resolution of 1cm and a range resolution of seven millimeters. Unfortunately, due to the price and extremely fine mechanical considerations, this system is not available in commercial market.

During the recent years, a new category of methods for standoff detection is devised, named non-imaging methods. References [20-21] has introduced a half-polarimetric radar named MiRTLE. This system can distinguish between different targets based on the cross polarization discrimination (Co-polarization to cross polarization ratio) of the targets. This system is a 77-105 GHz radar with 1cm range resolution.

In this paper, we propose a low cost radar system with a detection range of 15 meters. We use the ISM band near 24GHz because of the availability of low-cost commercially available transceivers and chipsets in this frequency band.

We have used chipsets with center frequency of 24.125MHz and bandwidth of 200MHz. The 200MHz bandwidth of the system yields a one-meter range resolution.

The TRX is comprised of a two-channel transceiver and an antenna system. The two-channel transceiver includes a PLL, transmit and receive circuitry and a processor board. The antenna system is comprised of a 52cm wide reflector antenna and two dual-mode horn antennas with excellent cross polarization characteristic.

In section II, we explain the general configuration of the radar. In section III, design and specification of antenna subsystem is discussed. Section IV shows a two-step test for calibration of the antennas. In section V, polarimetric behavior of human body is examined. Finally, in section VI we examine the performance of system.

II. General Configuration

Fig. 1 shows architecture of the system. The RF subsystem is a heterodyne phase-locked FMCW transceiver with one transmit and two receive ports. Mini EPIC is the two-channel processor of system with two inputs for two IF signals and one output port for feeding the LO input of the mixer at the output of TX stage.

This system utilizes one reflector antenna as the transmitter and two orthogonally polarized dual-mode horn antennas for capturing the reflected signal.

III. Antenna Subsystem

Early measurements emphasize that hands and edges of the body produces significant amount of cross polarization. Hence, the transmitter antenna must mostly illuminate the torso to avoid unwanted cross polarization geneartion. One can easily calculate that for a distance of 20 meters and 30cm width of the torso, diameter of the antenna must be about 50cm.

In order to ensure the low cross polarization level of the system, transmitter and receiver antennas must guarantee at least 30dB cross polarization discrimination in 3dB beamwidth angles. We used a choke ring antenna for obtaining maximum efficiency and ensuring the low cross polarization level in wide angle.

Fig. 2 shows the co-polarization and cross-polarization radiation pattern of the reflector antenna in 45° cut. The minimum obtained cross polarization discrimination is 28 dBi.

The receiver antennas are 24dBi dual-mode circular horn antennas. Designed dual-mode horn antennas ensure low cross- polarization lever in ±5° beamwidth.

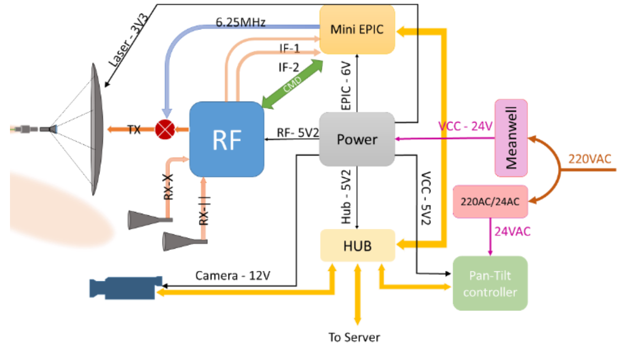

Fig. 1. Configuration of subsystems and modules

This wide-beamwidth operation reduces the susceptibility of cross polarization channel to displacements, considerably. Fig. 3 exhibits the measured co- and cross-polarization radiation pattern of a horn antenna in 45° cut.

Fig. 4 illustrates the placement of transmit and receive antennas. A laser pointer is embedded at the back of feed antenna to make sure that laser and reflector antenna point to the same direction. An IP camera is placed between horn antennas for image processing purposes.

IV. Calibration

The calibration of system is performed in two simple steps:

1. Pointing test
2. Sphere test

In the first step (pointing test), we ensure that laser pointer and reflector antenna point exactly to the same points. The radar transmits the signal to an aluminum trihedral and finds the direction with maximum signal reflectance. Then we adjust the laser to point to this direction.

In order to check the orthogonality of receiver antennas and measuring the minimum detectable cross-polarization level, we use a metallic sphere as the device under test. Metallic spheres do not change polarization of the transmitted signal and are ideal for this test. One can check that even a small rotation of the cross-polarized receiver antenna can change the level of measured cross polarization signal considerably.

After pointing the radar toward the sphere, we rotate the cross-polarized horn antenna until we obtain the minimum level of the cross polarization signal. Now we can make sure that antennas are orthogonally polarized.

V. Polarimetric Behavior of Body

At first, we examine the polarimetric behavior of the body to make sure that cross polarization of the body has negligible effect on the polarization of the reflected signal. Three different transmit polarizations including horizontal, 45° slant, and vertical polarizations is tested. Early measurements show that raising hands changes the cross polarization level considerably. Therefore, these tests are performed in two styles named hands-up and hands-down. Fig. 5 shows the two styles.

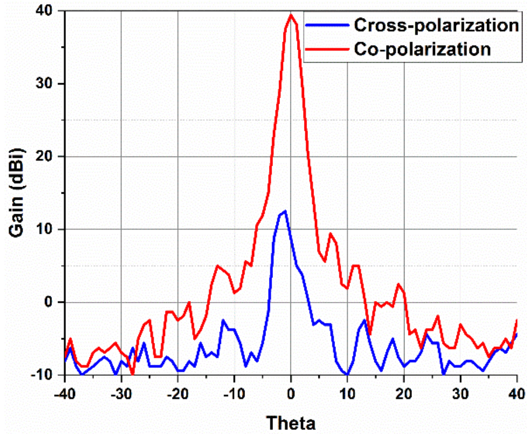

Fig. 2. Measured radiation pattern of the reflector antenna in 45° plane a) co-polarization in red b) cross polarization in blue

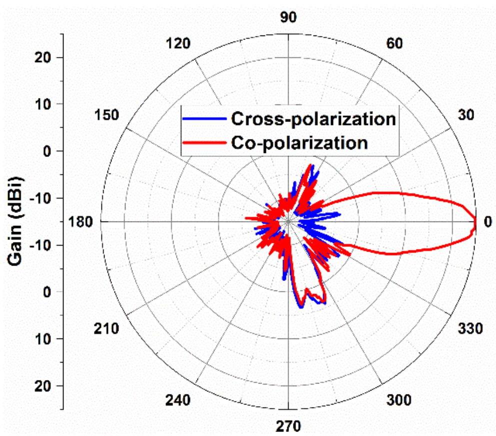

Fig. 3. Measured radiation pattern of reflector antenna in 45° plane a) co-polarization in red b) cross polarization in blue

Fig. 4. Image of placement of transmitter reflector and two receiver antennas

The measurement results for studying polarization behavior of the body is summarized in Fig. 6. This figure shows the cross polarization discrimination of the body for three different polarizations in two different styles.

It shows that XPD (cross polarization discrimination) improves in the hands-up style. In horizontal polarization, it improves by 5dB, in 45° slant polarization improves by 7 dB, and for vertical polarization, this improvement is negligible.

Therefore, due to lower susceptibility to style of the hands, the vertical polarization transmission is preferred.

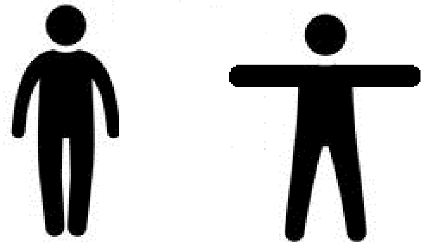

Fig. 5. Hands down (left) and hands up styles (Right)

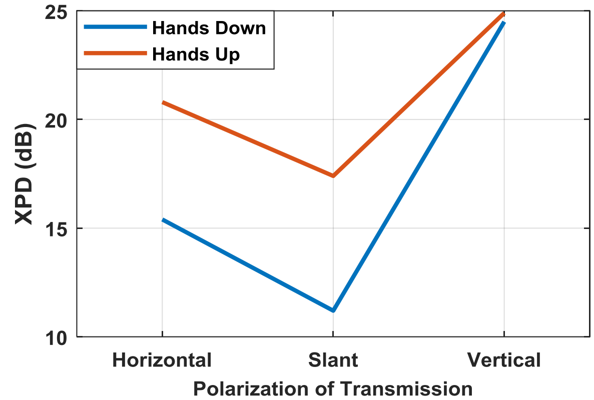

Fig. 6. Co-Polarization to cross-polarization ratio for two styles

Hence, choosing vertical polarization transmission guarantees 25dB cross polarization discrimination, regardless of styles of the hands.

VI. RESULTS

The concealed belt contains shrapnel for increasing the casualties. The shrapnel produces cross polarization. Even without any shrapnel, the detonation wires create cross-polarization effects. Fig. 7 depicts a fabricated sample of the belt.

The system interrogates the torso of a moving human target in two situations: when carrying the belt (called with-belt) and not carrying the belt (called no-belt).

The sampling rate is 10MS/sec, and after averaging in a 2.7mSec, it reduces to 360 samples per second. We performed the tests on different peoples for 400 seconds.

Fig. 7. A sample concealed belt under clothing

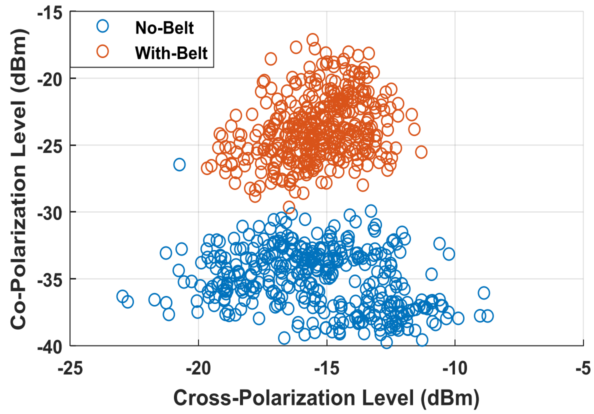

Fig. 8. Co-polarization versus cross-polarization (integration time=1sec)

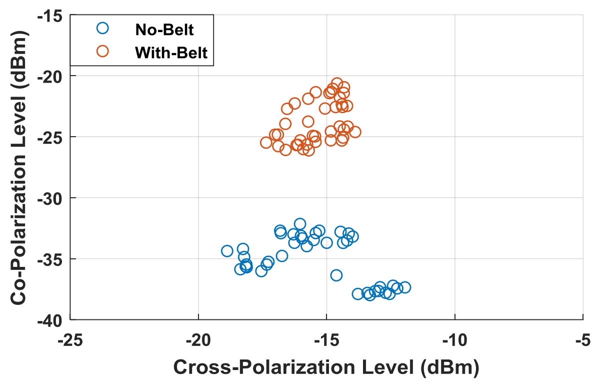

Fig. 9. Co-polarization versus cross-polarization (integration time=10 sec)

Fig. 8 demonstrate the cross-polarization versus co-polarization level for with-belt and no-belt situations in red and blue colors, respectively. The tests are executed at the distance of 15 meters for vertical polarization and integration time of one second.

Fig. 8 clearly shows that with-belt situation is distinguishable from no-belt situations by defining a threshold on XPD. If XPD less than threshold is the safe region and XPD more than threshold is threat region.

By increasing the integration time, the accuracy improves. Fig. 9 shows the results with integration time of ten seconds. It shows that in this case, the no-belt and with-belt situations are excellently separated.

For a better comparison, probability of false alarm and probability of detection for integration times of 0.2 to 10 seconds are shown in Fig. 10 and Fig. 11, respectively. As expected, increasing the integration time increases the Pd and decreases the Pfa. For example, threshold level of 12dB and integration time of 0.2 second yields Pfa of 0.08 and Pd of 0.8. By increasing the integration time from 0.2 second to 2 second, Pfa decreases to 0.004 and Pd increases to 0.92.

Pfa and Pd can vary based on the length and volume of the wires and the presented results show tests for a typical belt.

The radiation pattern of the transmitter antenna is axisymmetric and illuminates a circular portion of the torso. Since the shape of torso is more like a rectangle, an elliptical

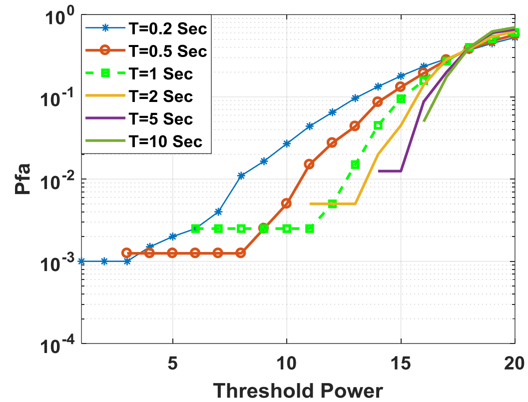

Fig. 10. Probability of false alarm vs. threshold for different integration times

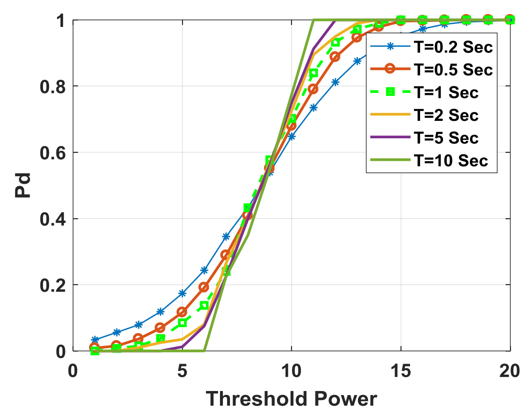

Fig. 11. Probability of false alarm vs. threshold for different integration times

beam is the ideal radiation pattern. Therefore, beam shaping methods can be applied to the design of reflector antenna. The authors [22,23] have introduced a method for the design of doubly curved shaped reflectors. Doubly curved reflectors are a category of antennas with narrow elliptical radiation pattern.

This results show that this method is an effective tool for threat detection. Several improvement in system are in progress. The improvements include replacing the two receive antennas by a dual-polarized antenna and implementing the coherent version of the radar for reducing the clutters and increasing the accuracy.

VII. Conclusion

We introduced a polarimetric radar for standoff detection of the threat based on the commercially available FMCW components. The system was tested for standoff distances up to 15 meters. We presented the structure and performance of different parts of the system. An antenna system provides the minimum cross-polarization discrimination level of 30dB. Numerous tests for studying polarimetric behavior of the body was performed and vertical polarization was chosen as the optimum transmission polarization. We showed that by introducing a threshold on XPD ratio, threats can be distinguishable from safe targets. Two systems were tested and we showed that the system (system with closely located receiver antennas) offer enhanced performance.

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