Foreign Objects Debris Detection (FOD) on Airport Runways Using a Broadband 78 GHz Sensor

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***Abstract*— This paper describes a compact broadband (73-80 GHz) mm-Wave front-end used for FOD detection application. The design philosophy of our system is to have several low-profile, low-cost mm-Wave sensors placed along the runway. Tests were conducted on the small airport of Aix Les Milles (south of France). High sensitivity and simultaneous objects detection capabilities were shown. Even very small objects like nuts were seen. The extension of the actual detection range is needed in order to go from 110 m (in the most favourable case) to 500 m.**

I. Introduction

Since a few years, Foreign Object Debris (FOD) detection on airport runways has become of increasing interest. A basic motivation for this is the fatal accident with a CONCORDE aircraft a few years ago due to a metal part lost by an aircraft on the runway some time before. Among the existing systems, we find those based on optical sensors like CDD cameras [1] or Ladar [2] and those based on mm-Wave radars [3-4].

In the last decade, microwave and mm-Wave system have found increasing commercial applications and gained importance in comfort and security applications like in automotive radar sensors in the 77 GHz frequency range [5-6]. Such sensors are equipped with narrow beam antennas for a good lateral resolution and a reasonably high bandwidth for a high range resolution. Detection range for automotive applications presently is 200-250 m, but in some projects, like power line detection for helicopter radar [7] much higher detection distances have been demonstrated with increased transmitter power and higher gain antennas [8]. Due to an increasing maturity and availability of circuits [9-11] and components for such systems, mm-Wave radar become more and more compact while being less expensive. Therefore, other applications, like FOD detection are within the range of realization.

In this paper we investigate the capabilities of FOD detection of a 73 – 80 GHz sensor. The choice of the frequency range is done according to the range assigned by the respective authorities, previous research experiences and the availability of key components. Furthermore an imaging radar sensor at sufficiently high frequency shall be able to detect relatively small pieces of metal, concrete, stone, or even plastic on an otherwise quite flat surface. Tests objects were selected and measurements were conducted on the French airport of Aix les Milles.

Section II describes the mm-Wave module and section III deals with measurements and discussion.

II. Mm-wave radar module and post-processing

A FMCW radar sensor (Frequency Modulated Continuous Wave) operating at frequencies from 73 GHz to 80 GHz was used for the FOD detection. A block diagram of the sensor is shown in Fig. 1.

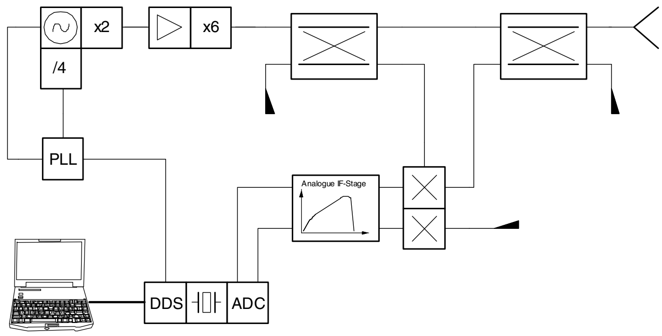

Fig. 1: Block diagram of the FMCW sensor used for foreign object detection.

The mm-Wave circuit of the sensor comprises a VCO operating at app. 6.4 GHz. A built-in frequency doubler and an external active multiplier generate the transmitted signal in the desired frequency range. The first coupler splits the signal to the transmit path and the LO port of the dual channel mixer. The second coupler acts as transmit- / receive duplexer which connects the transmit path to the antenna and the receive path to the input port of the mixer. Range compensation and anti aliasing filtering is performed in the analogue intermediate frequency (IF) stage. The second receiver path was not used in this setup and therefore matched with a waveguide load.

A. Synthesizer and data acquisition

The core of the FMCW sensor is a synthesizer based on a PLL and direct digital synthesis (DDS). The linear frequency modulated base band signal is digitally generated at frequencies lower than 25 MHz. This signal serves as reference signal of a phase locked loop (PLL) which controls the VCO mentioned in the last section. An important feature of the sensor is that the clock for the DDS and the analogue digital conversion unit (ADC) are both derived from the same crystal oscillator. Therefore not only the frequency synthesis but also the data acquisition are phase-locked to a very stable reference. This offers the possibility to coherently sum up subsequent radar measurements and in consequence improve the signal to noise ratio.

B. Antenna and sensor integration

To complete the sensor setup a planar folded reflectarray antenna [5] was attached to the mm-Wave module (Fig. 2).

Fig. 2: Sensor with planar folded reflectarray antenna.

The antenna's diameter is 130 mm and the measured gain in the operating frequency range is in the order of 35 dBi. Due to the fact that a pencil beam antenna was used for these first studies, the beam had to be geared towards the target for each measurement. In the final application this antenna will be replaced by an antenna with a cosec shaped beam.

C. Signal Processing

Processing of the IF signals is done in a manner which is typical for FMCW sensors. The sampled data are weighted using a Chebyschev window. Following this, a fast Fourier transform (FFT) is applied to calculate the range profile.
Additionally the overall coherency of the system makes it possible to calibrate the sensor by acquiring an empty scene measurement and subtracting these data from the actual measurements. This considerably improves the signal to clutter ratio and enables to detect targets with a very small radar cross section (RCS) such as metallic spheres or small screws.

III. MEASUREMENTS AND DICUSSION

The design philosophy of our system is to have several low-profile, low-cost mm-Wave sensors placed along the runway while respecting runway constraints, in particular, the zone where no device can be implemented. In order to test the FOD detection capabilities of a single mm-Wave module, two series of measurements were conducted:

- Preliminary measurements for knowing the radar performance,
- FOD measurements done on the airport of Aix les Milles

A. Preliminary measurements

Preliminary measurements were conducted on a car park in Ulm in November 2007. The first test consisted in estimating the radar detection range and to do preliminary FOD classification. What we call here classification consists in ranking the objects from the easiest to the most difficult to detect. For this purpose, several objects were selected according to their material, size and shape.

Fig. 3 shows the objects having particular shapes, the other are listed in Table I with the distance where they were detected and the sensibility of the detection regarding their position on the ground.

According to the radar equation [12], the radar cross-section of an object depends on (assuming a monostatic radar like in our case):

- The distance to the radar,
- The material the object is made of,
- The antenna polarization,
- The frequency,
- The incidence angle on the object (same as its position on the ground).

An object will be classified as easy to detect if it is not too sensitive to these parameters.

(a) Curved piece of metal

(b) Piece of tyre (10 cm)

Fig. 3: Test objects used for maximum range detection.

TABLE I
RANGE ESTIMATION

Objects	Rmax/Position
Metallic plate: 20 cm*30 cm*0.5 cm	Not detected
Metallic plate: 20 cm*30 cm*3 cm	100 m/horizontal 50 m/45°
PVC plate: 20 cm*30 cm*3.5 cm	50 m/horizontal 50 m/45°
Curved piece of metal (Fig. 3 a)	110 m
Piece of tire (10 cm) (Fig. 3 b)	90 m
Wood bloc: 22.5 cm*7 cm*7 cm	110 m
Metal cylinder r=3 cm, l=19 cm	110 m
Nut, h=21 mm, 10 mm thick	40-30 m
Screw, l=6.5 cm, hexagonal head 17 mm	90 m/vertical 40 m/horizontal
Metallic sphere	90 m, r=2.25 cm 40 m, r=1.25 cm

The maximum detection range is 110 m and is currently limited by the IF stage of the system. Almost all of the objects have been seen. Some of them, like cylinders, are easy to detect whereas the detection of the plates is strongly sensitive to their orientation and thickness. Fortunately, the most dangerous part, (Fig. 3 a), was detected.

B. FOD measurements on the airport of Aix Les Milles

FOD measurements were conducted in December 2007 on the small airport of Aix les Mille in the south of France. In this experiment, several objects were placed on the runway (Fig. 4). They were selected as being relevant for FOD application. There are tools, screws, nuts and pieces of metal that were chosen because they are parts of objects that could be forgotten by the runway operators or might fall from the airplanes. They are listed below:

- O1: cutting pliers 18 cm long,
- O2: rectangular 17 cm*3 cm metal ruler,
- O3: cardboard box with corner reflectors,
- O4: M-10 nut,
- O5: red plastic pencil 14 cm long, 1 cm diameter,
- O6: sphere, r=2.25 cm,
- O7: tea box 10 cm*12 cm*9 cm,
- O8: Metallic plate: 20 cm*30 cm*3 cm, turned 16° on the runway.

All the objects were placed simultaneously on the runway. Manual scans were conducted at distances of 30 m (Fig. 5) and 20 m (Fig. 6).

Fig. 4: Test site of Aix les Milles.

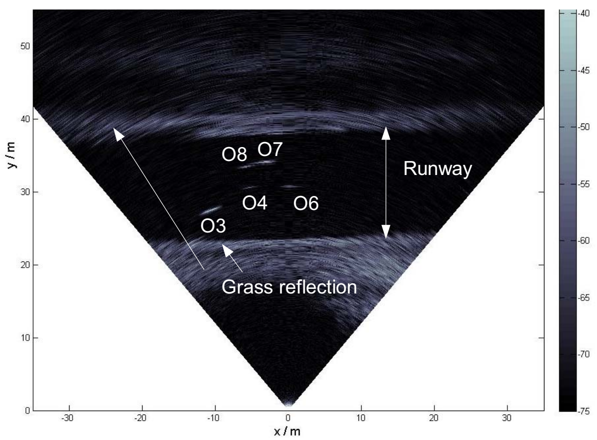

Fig. 5: Radar image obtained with manual scan at 30m.

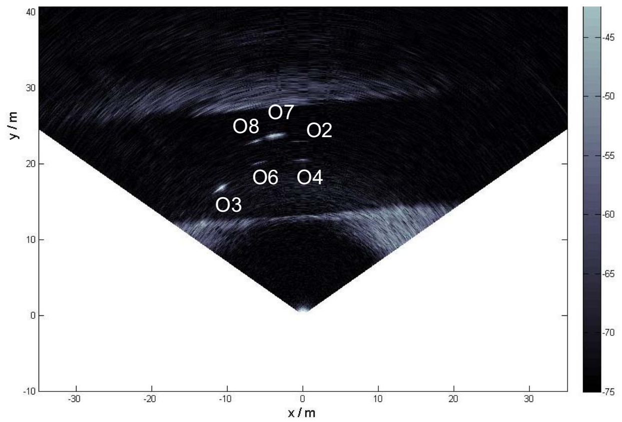

Fig. 6: Radar image obtained with manual scan at 20m.

Almost all the objects, including the smallest like the nut, were detected at 30 m distance except the pencil. The ruler (O2) appears at 20 m. Unfortunately, the cutting pliers were placed outsides of the scan. In addition, we could see the strong reflection from the grass outsides of the runway.

C. Discussion and future work

First of all, with detection capability of very small objects while being very compact, the designed mm-Wave front-end has proven to be a good candidate for FOD detection applications. Nevertheless, with about 5 mW emitted power, the detection range is actually too small for an airport implementation. Future work will consist in:

- Pushing the emitted power from 5 mW to 100 mW while keeping a low cost module,
- Designing a high gain scanning antenna system comprising a cosec antenna.

Further improvements will be done by optimizing the sensor, e.g. by further reducing phase noise and other effects limiting the present sensor sensitivity.

Secondly measurements have shown that some objects are very difficult, not to say impossible to detect. Our tests pointed out that the overall size is not the critical factor since the very thin plate (typ. < 5 mm), with a large (compared to wavelength) area, was much more difficult to detect than the nut. Remembering that a metal slide caused the Concorde crash in 2001, one has to work on these particular shapes. In this case, increasing the emitted power is not sufficient because the main problem is the object diffraction. Indeed, in the case of the thin plate most of the incident energy is diffracted in the specular direction whereas there is more reflection when the thickness increases. If mono- or weak bi-static radars are used, the received signal from the target will be too low in most cases. To overcome this problem one could use a multi-static configuration provided that we could solve the problem of synchronising all the mm-Waves modules. Although we focus on the mm-Wave radar module, additional system improvements could be obtained while performing data fusion from the mm-Wave radar and an optical sensor (for example infrared camera).

IV. CONCLUSIONS

A compact and low-cost broadband 73-80 GHz mm-Wave module was designed for FOD detection applications and tested on the small airport of Aix Les Milles. High sensitivity and simultaneous objects detection capabilities were shown. An extension of the actual detection range is needed in order to go from 110 m (in the most favourable case) to 500 m. The final setup will consist of several modules covering the entire runway. In addition, in site measurements have shown that future investigations should focus on the detection of thin objects that are the most difficult ones to detect.

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