

RESEARCH PAPER

A multimodal sensor system for runway debris detection

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For foreign object detection on runways, highly sensitive radar sensors give the opportunity to detect even very small objects, metallic and non-metallic, also under adverse weather conditions. As it is desirable for airport applications to install only small but robust installations along the traffic areas, millimeter-wave radars offer the advantage of small antenna apertures and miniaturized system hardware. A 220-GHz radar was developed, which is capable to serve this application, if several of these are netted to cover the whole traffic area. Although under fortunate conditions the radar allows a classification or even an identification of the debris, the complete system design incorporates 3-D time-of-flight cameras for assistance in the identification process, which are also distributed along the traffic areas. The system approach further relies upon a change detection algorithm on the netted information to discriminate non-stationary alarms and reduce the false alarm ratio.

Keywords: Millimeter-wave radar, Multisensory system, Time-of-flight camera, Change detection, Runway debris

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I. INTRODUCTION

The detection and classification of runway debris is a major concern for airport operation, as related flight delays and accident claims as well as aircraft repairs are very costly. In forthcoming years traffic on airports will even increase and thus the demand on maintaining an adequate safety level. For safe airport operation it is necessary that the runways and taxiways are permanently in an undisturbed condition. Following the recommendations of the International Civil Aviation Organization (ICAO), the inspection of runways is currently done at a period of 6 hours, visually by security personnel. This procedure is costly and may be subject to human failure and is also highly dependent on weather and daylight conditions. Especially at adverse weather the visual inspection cannot guarantee the detection of small metallic particles such as screws. Moreover, the traffic density on airports has been considerably increasing, and a secure inspection between consecutive take-offs and landings by human visual inspection is not possible.

A few automatic or semi-automatic systems have been proposed or are in use at some airports to serve this purpose [1]. Video surveillance is one of the proposals, but suffers from obscuration by bad weather. Radar sensors, which are

capable to be operated under all weather conditions [2], are also taken under consideration.

II. MULTI-SENSOR SYSTEM FOR DEBRIS DETECTION

The approach discussed in the following takes advantage of both sensors. Millimeter-wave radar is used for detection and pre-classification, while 2D–3D time-of-flight (TOF) cameras give additional information on detected debris, if the environmental conditions allow this.

The LAOTSE [3] concept is based upon a net of miniaturized 220-GHz radar modules, which are positioned along the traffic areas. The 220-GHz band is used, which in comparison to lower frequencies allows considerably smaller antennas with high directivity and thus a miniaturization of the complete set-up. Furthermore, a wider bandwidth and thus a higher ranger resolution can be accommodated at higher frequencies. Using the available 220-GHz-radar modules the range of each sensor is limited to about 300 m, which allows a coverage of 1/2 km of runway. A netted approach is necessary as the output power of each radar is not sufficient to cover the whole traffic area, and additionally the probability of false alarms is considerably reduced for areas, which are monitored from different aspects. The information content of neighboring, overlapping, and in the end of all radar sensors has to be merged and aligned using overlapping segments of the surveyed area. The total LAOTSE system is additionally using distributed photonic mixer device (PMD) [4] cameras, which are focused on objects, which

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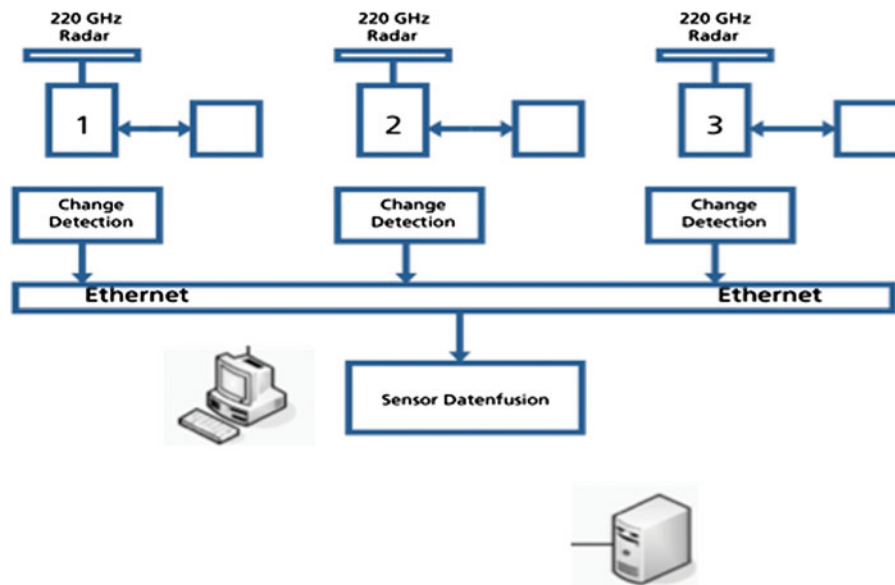


Fig. 1. Demonstrator set-up with three radar front-ends.

have been detected by the radar and are also part of the sensor net. Figure 1 shows a sketch of the total sensor set-up.

III. THE RADAR CONCEPT

A) Radar geometry

Tests of an experimental LAOTSE system, with a limited number of sensors, are conducted on the Cologne-Bonn “Konrad-Adenauer” Airport (Fig. 2).

The first LAOTSE radar module is mounted at a slightly elevated position near to the crossing of the old runway and the cross-wind runway to be able to overlook a certain area. Figure 3 demonstrates the geometry. Figure 4 shows the illumination by the antenna beam.

To miniaturize the system, the 220-GHz frequency band is used, which allows to reduce the antenna diameter by more than a factor of two. This is essential for operation in an

airport environment, where obstacles like the netted sensors along the runway have to be avoided. This approach, however, demands for a wider net of sensors to cover the complete runway area. For complete demonstration of LAOTSE performance, a second sensor will be installed along the old runway to maintain an overlapping survey region. In the following, the approach for a single radar module is described.

B) 220-GHz sensor front-end

The system concept is based on a design, which was already realized at 94 GHz [5]. The radar frequency modulation continuous wave (Radar) (FM-CW) front-end uses miniaturized, monolithically integrated components in GaAs technique [6]. In order to cover a bigger range, such as 200 m, coherency of the signal is most essential. The classical FM-CW approach uses a reference signal, which is derived from a voltage controlled oscillator (VCO), which for millimeter-wave systems generally is not stable enough to maintain the necessary



Fig. 2. Photo of Cologne-Bonn Airport with LAOTSE Site, old runway (below) and cross-wind runway.



Fig. 6. Photo of a 220-GHz LAOTSE radar front-end.

measuring the elapsed time. Hence, ToF is – quite similar to a radar – an active ranging system that needs an illumination source. Basically, a ToF camera emits continuously a light signal with a constant wavelength. Mostly, the near-infrared area is used for this purpose, because it is invisible and simultaneously not harmful for the human eye (Fig. 8).

To measure distances, the light has to be modulated adequately. Then, it is possible to evaluate it as the modulation of the back-scattered signal differs from that of the emitted one. ToF cameras usually modulate their carrier signal by a harmonic oscillation with the frequency f . Then, the phase difference is given by

$$\Delta\phi = 2\pi f \frac{2R}{c}, \tag{1}$$

where R denotes the distance between transmitter and reflecting object and c is the speed of light. Transmit and receive

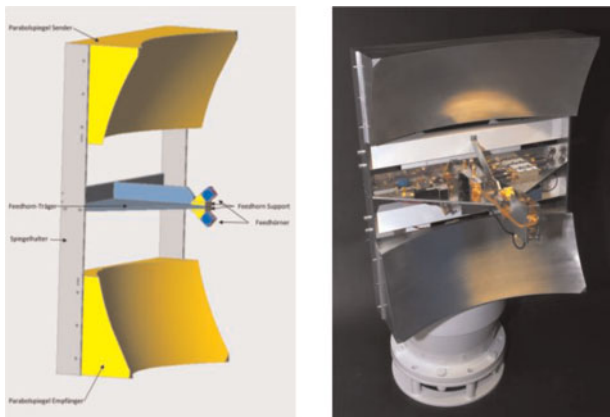


Fig. 7. Sketch of antenna assembly and photo of radar upon pedestal.



Fig. 8. PMD CamCube consisting of camera and illumination unit.

signals are mixed for each individual pixel of the sensor matrix that allows the determination of the phase difference, i.e. by sampling of the obtained correlation function at four time samples with the values A_1, A_2, A_3, A_4 each shifted by 90° [7]:

$$\Delta\phi = \tan^{-1} \frac{A_1 - A_3}{A_2 - A_4}. \tag{2}$$

Then, the range is calculated by (1). If the modulation frequency is stable enough, the integration time can be chosen comparably high to improve the signal-to-noise ratio. However, the choice of the modulation frequency f is crucial as it directly constraints the maximum range. Only phase differences of $0 \leq \Delta\phi < 2\pi$ within one period can be used for

$$R_{unamb} = \frac{c}{2f}. \tag{3}$$

Commercial ToF cameras often operate with a modulation frequency of 20 MHz, yielding a 7.5-m-long measurement area. In order to increase this, signal processing techniques, as known from image processing for radar interferometry, can be applied to evaluate the phase information of adjacent pixels. Such 2D phase unwrapping methods allow an unambiguous phase determination over multiple periods [8]. Another option would be to use multitone techniques as they are known from automotive applications [9]. An overview about the technical specifications is given in Table 1. The camera lens is changeable and thus customized for different applications, such as for automotive applications,

Table 1. Performance parameter of PMD camera.

Parameter	Value
Standard range	0.3–7 m
Repeatability (1σ)	3 mm
Frame rate	40 fps at 200×200 pixels 60 fps at 176×144 pixels 80 fps at 160×120 pixels
Field of view	$40^\circ \times 40^\circ$
Illumination wavelength	870 nm
Power supply	$12\text{ V} \pm 10\%$
Interface	USB 2.0

Table 2. Sample objects used for ISAR measurements.

Objects		
Tools	Metal pieces	Dielectric pieces
Pliers	Wire bundle	Plastic 100 mm × 40 mm × 35 mm
Screw driver	Screw M8 × 60	Plastic tray 2 shelf
Folding ruler	Metal bar 30 mm × 30 mm × 30 mm	Plastic tray 3 shelf
File	Wheel $d = 75$ mm	Wood pieces 100 mm × 40 mm × 20 mm
Saw	Antenna fixing	Stone
Paint brush	Metal plate 200 mm × 15 mm	Cable channel (plastic)

long-range surveillance, or medical applications (short-range surveillance).

V. TEST MEASUREMENTS

A) Inverse synthetic aperture (ISAR) measurements at 220 GHz

To test the sensitivity of the system and to evaluate the range under which small items can be detected, measurements with an assembly of 25 different small objects on a turntable at a



Fig. 9. Test objects on turntable.

range of about 200 m were conducted. The objects were turned over 360°, and the measured data were evaluated using an ISAR algorithm, which, in contrary to the final LAOTSE algorithm gives a synthetic radar image of each object. Table 2 gives a catalogue of the measured objects. Figure 9 shows a photo of the assembly of parts on the turntable.

Before the measurements, the system was calibrated by means of a trihedral corner reflector, which was positioned in the middle of the turntable. This allows a thorough phase calibration, which is necessary for the ISAR process and at the end allows to assign a distinct radar cross section to each item on the turntable. Figure 10 shows ISAR images for an aspect angle range of 360 and 10°. The latter is less than typical for the LAOTSE geometry. The evaluation showed that all small items could be detected and imaged independent of aspect angle. Only for dry wooden blocks this did not apply, as they could be seen only at those angles, where they were facing the radar. If they were only a little bit humid, they were also visible for all aspect angles. Resolution does not play an important role and the detectability is not influenced by a resolution range between 2 and 8 cm. It can be concluded that for an operational system a resolution of about 10 cm is fully sufficient.

B) LAOTSE radar measurements

While for the test measurements, described above, the radar was fixed and the objects were turning to be visible for all aspect angles; further tests were conducted with the operational geometry of a scanning radar. By chance the weather was very bad with low visibility during the measurements. Figure 11 shows a photo of the measurement scene. Figure 12 shows the result of a sector scan. Clearly, the fence surrounding the terrain can be identified by its very strong radar echo (red) and the returns of some small items in front of the fence.

C) Measurements with the PMD camera

The combination of radar technology and optical systems facilitate a reliable surveillance of runways. To demonstrate this, a ToF camera from PMD Technologies GmbH was

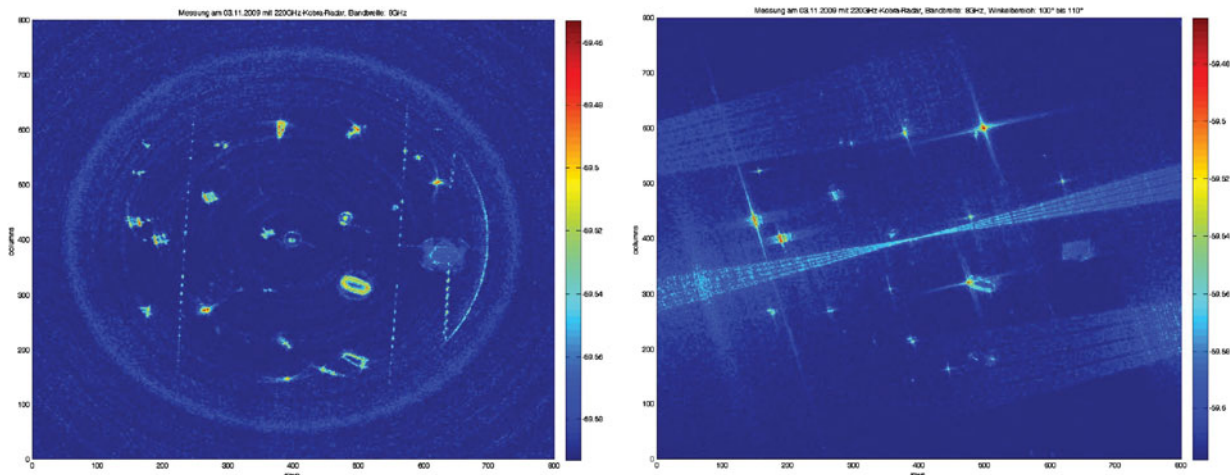


Fig. 10. ISAR image of sample objects for 360 and 10° aspect angle range.

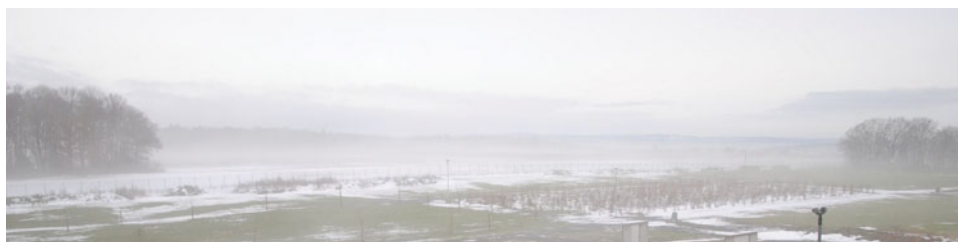


Fig. 11. Measurement scene at Fraunhofer FHR.

used to image different objects and materials on a smooth plane. To demonstrate the potential of such a ToF system, a 870-nm PMD camera comprising of about 200×200 pixels was used to image different objects and materials, as demonstrated in Fig. 13.

To obtain detailed and undistorted images a free-space measurement has to be carried out with the camera system, which will be subtracted from the following measurements. This is a similar idea as for the surveillance radar, which detects objects using change detection methods. Only deviations from frame to frame in the signature of the surface of the runway are imaged. Thereby the range increase in dependency of the aspect angle, as well as the intensity variation within the illumination spot can be removed.

Different objects and materials have been imaged. The objects can be identified easily by their shape. This allows a reliable evaluation of the threat on the runways by the airport personnel which can decide, whether a removal is mandatory or not as in the case of a non-dangerous item such as a piece of paper. As described in the section above, ToF cameras are able to measure 3D objects. To illustrate this, the scissors from the test set-up in Fig. 13 have been selected exemplarily. Figure 14 shows the result. The height information is coded by the red color. The bars as well as blades are depicted in a clear way, such that the item can be identified as scissors. The range deviation could be compensated successfully as the object is imaged on a constant elevation. It should be mentioned that both measurements can also be carried out under foggy or rainy conditions making the system very attractive for a non-stop operation.

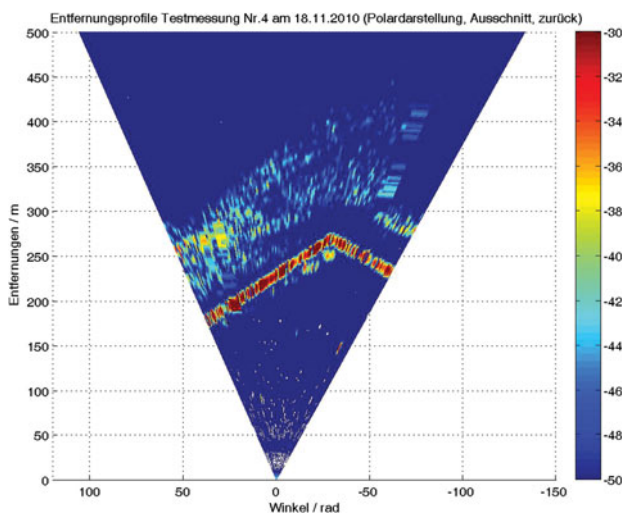


Fig. 12. Sector scan for test scene.

VI. SENSOR DATA FUSION

The miniaturization of the antennas leads to a netted setup of multiple radars to cover the whole runway. The detection of foreign object detection (FOD) is done by change detection separately for each sensor. The geometric data fusion between all netted sensors could be done using the position and attitude of each sensor. In this approach the position and attitude must be exactly known, to treat them correctly in a geometric transformation process. To overcome this limitation the overlap regions between the sensors can be used. The relatively high resolution of the sensors allows to treat the radar data as images. Adjacent radars produce images with an overlap region. With this region a matching in the image plain can be performed. The first step is to detect feature points in every radar image. Possible feature detectors are the Harris detector [10] or the scale invariant feature detector [11]. These feature points can be matched to another. With these matches an affine transformation between two images can be computed. This procedure can be easily scaled to an arbitrary number of sensors. The benefit of this approach is the independence of the sensor geometry. In comparison with the first approach, only the position and attitude of one sensor is needed to project the detection result on the runway, while the position and attitude of the other sensors can be unknown.

The overlap region can be also used to improve the detection results. It may occur that the radar cross section of an FOD is so small that it is not detected through the change detection. If this happens in an overlap region, then it is highly possible that it can be detected by its adjacent sensor. This can also decrease the false alarm rate of the system and increase its probability of detection.



Fig. 13. Sample assembly of small objects for PMD camera tests.

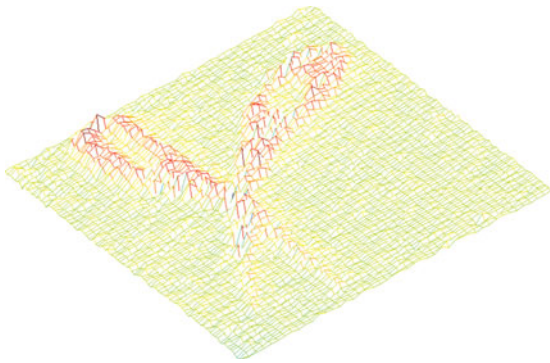


Fig. 14. 3D image of the scissors from Fig. 13.

VII. CONCLUSIONS

An innovative solution for runway surveillance and debris reconnaissance was proposed. Millimeter-wave radar sensors as well as optical 3D sensors were fused to get as much information as possible and to achieve a high and reliable detection rate. The system supports the airport personnel responsible for the safety of aircrafts on runways during take-off and landing by giving an alarm in the case of a dangerous item on the runway. Radar modules at a frequency of 220 GHz were developed as elements for a netted set-up along traffic ways on airports. It was demonstrated that also under adverse weather conditions small objects, metallic and non-metallic, could be detected. The radar system monitors the runway in change detection mode and gives the fused information to the optical system that images the item in more detail. Test measurements showed the feasibility of this technique by using a ToF camera. Both the intensity plot as well as the 3D range image enabled a clear identification of objects.

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