Perimeter Surveillance Using a Combination of Radar and Optical Sensors

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***Abstract*—A stand-alone perimeter surveillance system has been developed using a combination of radar sensors operating at 24 GHz and a HD pan-tilt-zoom camera. The system provides the capability to detect and track intruders across a monitored area even at poor view conditions.**

I. Introduction

A. Motivation

The effective surveillance of large critical areas is crucial for the security of airports, border checkpoints, military installations as well as sensitive industrial facilities. The main goal of perimeter observation is to detect, classify and optionally identify approaching targets such as persons, vehicles or even small animals. This must be done at any time of day independently of weather conditions. Additionally, an automatic target detection capability of a system can increase the reliability and save costs at the same time.

As each type of sensor has its strengths and weaknesses, a suitable combination of different technologies can be the answer to these requirements. Modern optical sensors provide an excellent resolution and sensitivity at good visibility conditions but show a limited performance at night and bad weather. In contrast, radar based sensors offer a much lower spacial resolution but provide the unique capability for accurate range measurements and work correctly at night, rain, snow and misty weather. Hence, a combined radar-camera approach can be a good solution for a reliable perimeter surveillance.

B. System Overview

The security system developed at IMST is based on four FMCW radar modules operating in the ISM band of 24 GHz (see section II-A). Together, the radar sensors fully cover a perimeter with a radius of 30 m (currently limited by the antenna beam) and an angular range of 180°. Each target appearing in the monitored area is detected and tracked by the system. Due to the high sensitivity of the used radar sensors, even small targets like birds are recognized as target objects. Additionally, the system is equipped with a high-resolution pan-tilt-zoom (PTZ) camera directed to the same observation area (see section IV-A). Depending on the current situation, the camera operates in one of two modes:

- **Tracking Mode**: The camera observes the complete area and tracks potential intruders using an advanced change detection algorithm. The targets found by radar and camera are fused to increase the detection probability and to reduce the false alarm rate.
- **Zoom Mode**: After a potential target was selected by the system, the camera zooms at the estimated position and follows the intruder across the monitored area. During this time, additional information (e.g. target features or even biometric data) can be extracted.

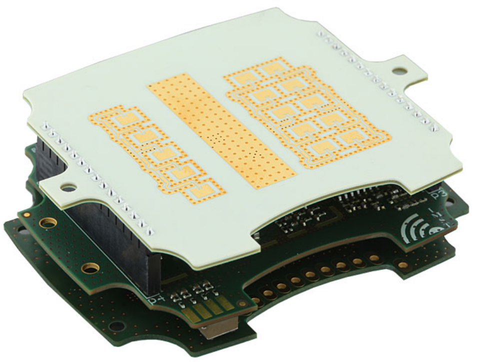

Fig. 1. IMST 24 GHz radar module sR-1200 without housing

II. Radar System

A. FMCW Radar Module

The radar sensor sR-1200 developed at IMST operates in FMCW (or alternatively CW) mode in the ISM band of 24 GHz. The restricted bandwidth of 250 MHz corresponds to a range resolution of approximately 60 cm, which is sufficient for detection and tracking purposes, but is not good enough to extract specific features from a detected person. The radar provides one transmitter (Tx) and two receiver (Rx) channels equipped with I/Q demodulators and A/D converters. In the presented application, integrated patch antennas with azimuth and elevation angles of 70° respective 24° have been used (see Figure 1). By evaluating the phase difference between both Rx channels, the direction of arrival of a reflected signal can be measured. Together with the range measurement capability of the system, this can be used to generate a 2-dimensional reflectivity map of the monitored area. A detailed description of the IMST radar can be found in [1], more interesting applications are presented in [2] and [3]. Table I contains the most relevant system parameters.

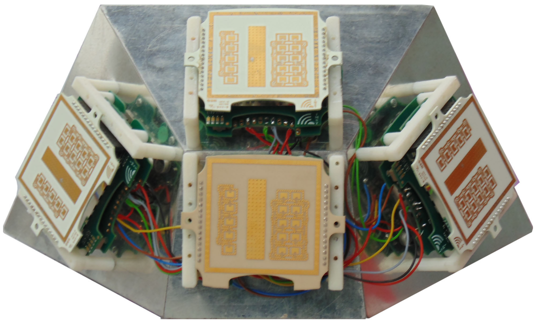

Fig. 2. Prototype of a sensor frontend equipped with four radar modules

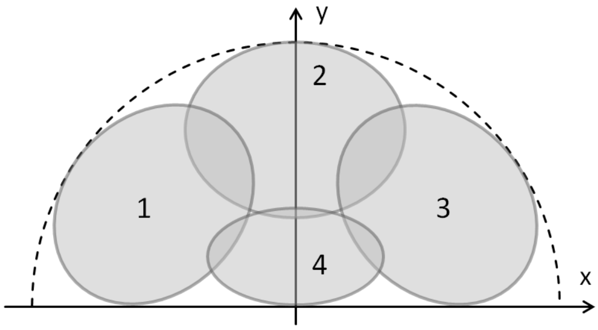

Fig. 3. Coverage of the surveillance area using four IMST radar modules

TABLE I
OPERATION PARAMETERS OF THE RADAR SENSOR

Parameter	Value
Frequency Range	24 GHz – 24.25 GHz
Output Power (EIRP)	20 dBm
Range Resolution	0.6 m
Azimuth Angle Accuracy	2°– 3°
Azimuth Beamwidth	70°
Elevation Beamwidth	24°
Polarization	vertical
Dimensions (with Housing)	75 mm × 80 mm × 40 mm
Weight (with Housing)	164 g
Power Consumption	5 W (Standby: 1 W)
Interface	SPI, CAN or Ethernet

B. Multi-Sensor Frontend

As the azimuth beamwidth of a single radar sensor is limited to 70°, at least three modules are required to cover the angular range of 180°. Additionally, another module is required to cover the near range area below the radar frontend. Figure 2 shows the multi-sensor frontend equipped with four radar modules, Figure 3 visualizes the arrangement of antenna beams inside the monitored perimeter.

The overlap of the antenna beams could possibly cause a crosstalk between different radar modules, resulting in reduced sensitivity as well as in increased false alarm rate. Therefore, the radar modules are operated in serial mode: only one RF frontend is transmitting at a given time. The main disadvantage of this principle is a reduction of the pulse repetition frequency by factor 4. After collecting measurement data from all radar modules the central processing unit performs some post-processing steps by merging the potential targets into one single data set (see section III-C).

III. Signal Processing

While the first processing steps of raw measurement data are performed by the DSCs of the radar modules (sections III-A and III-B), the concluding fusion of data streams is done by the central control unit of the system (section III-C). Figure 4 shows a simplified block diagram of module-internal signal processing steps.

A. Clutter Suppression

In order to achieve a sufficient sensitivity to detect low reflective targets (e.g. humans) inside a high reflective background (e.g. buildings, parking cars, fences), the static background (also known as clutter) must be removed from the measurement data. This is done independently for both Rx channels directly after sampling the IF signals. In a first step, the differential signal S_D is calculated using the formula:

$$S_D(t) = S_M(t) - C(t), \qquad (1)$$

where S_M is the sampled IF signal in time domain and C is the corresponding background signal. In a second step, the background (clutter) information is updated:

$$C^*(t) = \frac{C(t) \cdot (N-1) + S_M(t)}{N}. \qquad (2)$$

The parameter N determines how fast the background data stored in the DSC adopts to the measurement data.

B. Detection and Tracking

After a successful clutter suppression the radar data contains only contributions coming from noise and moving targets.

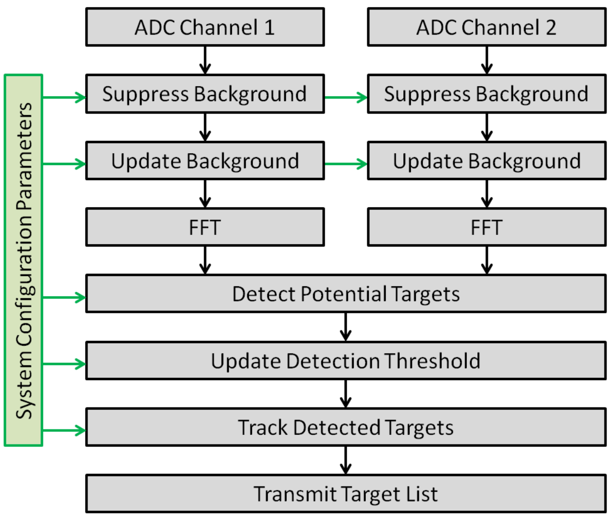

Fig. 4. Signal processing steps performed inside the radar module

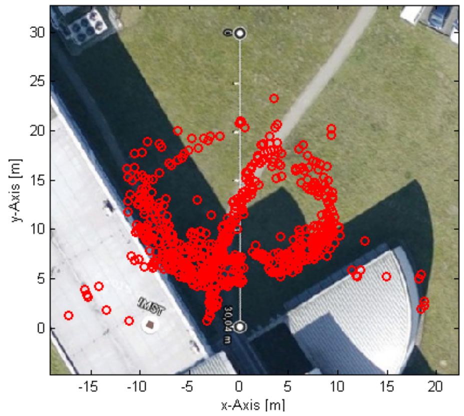

Fig. 5. Radar detections from a person walking across the monitored area (© Aerowest GmbH)

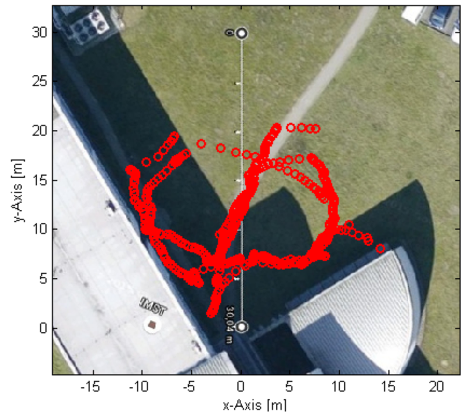

Fig. 6. Estimated position of a walking person after merging and processing of four transmitted detection lists (© Aerowest GmbH)

At this point, the data is transformed to frequency domain using a Fast Fourier Transform (FFT) of order 1024. After comparison of the signal spectrum $A(f)$ with a corresponding detection threshold $D(f)$, a number of potential targets can be identified. The detection threshold describes the expected noise level of the signal for each frequency respective range bin. As this value is not constant over time, it must be updated continuously during the measurement process:

$$D^*(f) = \begin{cases} \frac{D(f)\cdot(M-1)+A(f)}{M} & \text{if } A(f) < D(f)\cdot k \\ D(f) & \text{else} \end{cases} \quad (3)$$

Hereby, M is a filter constant (analog to N in equation 2) and k is a factor by which a valid detection must exceed the detection threshold. It should be mentioned that the threshold is not updated at the positions of detected targets.

Additionally, the new list of detections is passed to a tracker algorithm, which tries to assign them to a target list stored in the DSC memory. Hereby, three different cases can appear:

1) an existing target is confirmed,
2) a new target is found and added to list,
3) an old target is lost and (optionally) deleted.

The output data stream from a single radar module to the central control unit contains a list of detected and tracked targets with the following properties:

- unique target ID,
- radial distance from radar,
- view angle relative to radar line-of-sight,
- signal amplitude,
- life-time (how long is the target visible),
- status flag (new or confirmed target).

C. Target Post-Processing

The central control unit of the surveillance system collects the data sets transmitted by the four independently operating radar modules before performing the following post-processing steps:

- transforming the target coordinates to a common ground coordinate system,
- selecting the targets with the highest reliability (this can e.g. be done by maximizing the product of target's amplitude and its life-time)
- time filtering to suppress spikes and false alarms,
- final smoothing of target positions using spatial filtering.

Figure 5 shows the positions of all target detections resulting from a person walking across the backyard of the IMST building. It can be observed, that the limited angular measurement accuracy causes significant fluctuations of the estimated target position. Additionally, several false alarms appear in regions, where no targets can be expected (e.g. roof of the building). In comparison, Figure 6 visualizes the estimated target positions after the processing steps described above. This clearly demonstrates the system's capability to suppress false alarms as well as to create smooth and continuous target tracks, required by the optical camera.

IV. PTZ Camera

A. Hardware Description

In the presented perimeter surveillance system, the multichannel radar is combined with the commercial camera AXIS P5514-E [4]. This high resolution network camera is powered over Ethernet and provides full pan-tilt-zoom (PTZ) capability. The most relevant system parameters are summarized in Table II. In the current measurement setup, the camera was mounted approximately 2 m above the radar frontend covering the same observation area like the four radar modules.

TABLE II
Operation Parameters of the PTZ Camera

Parameter	**Value**
Resolution	HDTV 720p (1080×720)
Frame Rate	50/60 fps
Data Stream Format	H.264 or Motion JPEG
Optical Zoom	12× with Autofocus
Field of View	360° with Auto-flip
Interface	Ethernet (Power over Ethernet)

Fig. 7. PTZ camera operating in Tracking mode

Fig. 8. PTZ camera operating in Zoom mode

B. Tracking Mode

When operating in Tracking mode, the PTZ camera observes the complete area and looks for sudden changes in the data stream. Therefore, a background image is calculated and continuously updated by the system similar to the radar detection algorithm presented in section III-A. For target detection in visual images, different advanced algorithms can be applied, as finite set statistics [5] or box-particle probability hypothesis density filtering [6]. The analysis of visual data was performed using the software GekoSys developed and kindly provided by the Fraunhofer FKIE. Figure 7 shows a snapshot of the video stream during operation in Tracking mode.

C. Zoom Mode

After a potential target respective intruder has been detected and localized by the surveillance system, the PTZ camera switches to Zoom mode. In this operation mode the camera zooms into the scene (the zoom factor depends on the target distance) and "follows" the intruder across the monitored area. During this time, high resolution images of the target are produced, which can be use for classification and identification reasons. In case of a human intruder, even biometric data can be extracted. As main drawback of the Zoom mode can be mentioned that the camera loses the overview of the total monitored area while concentrating on the selected target. Nevertheless, this task is permanently fulfilled by the radar system, which always observes the complete perimeter. Figure 8 shows a snapshot of the video stream during zooming on a person at a distance of approximately 30 m.

V. Conclusion and Outlook

The perimeter surveillance system presented in this paper is based on a combination of optical and radar based sensors. Due to the complement capabilities of both technologies, the system is able to monitor a defined critical area at any time of day and any weather conditions. A potential intruder detected by radar or camera is tracked by the system across the scene in order to extract additional information, which can be used for classification or identification reasons. A fully automatic system control doesn't require a human operator and generates a remote alarm signal at the appearance of a defined critical situation.

In future, the development will be aimed at a better fusion of data coming from radar and optical camera. A new tracking algorithm (potentially including a Kalman filtering) will process and combine detections of both sensors to improve the accuracy of target tracking and to reduce the false alarm rate. Moreover, a special algorithm will prevent targets visible for a long time to be "absorbed" by the background and thus be lost by the system. These tasks as well as the fusion of radar and visual data will be performed in close collaboration with the Fraunhofer FKIE. In sum, the presented approach will lead to a further improvement of security at critical sites and facilities.

References

[1] IMST, "24 ghz fmcw multi-channel radar module," *Microwave Journal*, vol. 56, no. 12, pp. 92–94, Dec. 2013.

[2] R. Kulke, J. Kassner, T. Klein, and M. Seeger, "A polarimetric radar for soil roughness characterization flying on small rpas," in *Proc. International Radar Conference (Radar 2014)*, Lille, France, Oct. 2014.

[3] C. Ben, T. Islam, and D. Moormann, "Field study of a 24 ghz fmcw radar system suitable to detect small-sized rpas under 5 kg mtow," in *International Micro Air Vehicles Conference (IMAV 2015)*, Aachen, Germany, Sep. 2015.

[4] "Axis p5514-e ptz dome network camera data sheet," Axis Communications AB, Lund, Sweden. [Online]. Available: http://www.axis.com/files/datasheet/ds_p5514e_1502154_en_1509.pdf

[5] M. Schikora, W. Koch, and D. Cremers, "Multi-object tracking via high accuracy optical flow and finite set statistics," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP 2011)*, Prague, Czech Republic, May 2011, pp. 1409–1412.

[6] M. Schikora, A. Gning, L. Mihaylova, D. Cremers, and W. Koch, "Box-particle probability hypothesis density filtering," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 50, pp. 1660–1672, Jul. 2014.