Easily deployable, multi-functional radar network

This paper reports progress in the development of a micro-sensor wireless radar network for situational awareness in ground operations. The structure of the network and the sensors is described. Advantages over similar systems are discussed. Finally, an overview of the signal processing employed to execute different tasks of the system is presented along with some experimental results.

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Introduction

The capability of modern sensors to detect ground targets has increased interest in the development of a sensor network for defence applications such force and perimeter protection, border security and situational awareness. In these systems, seismic and acoustic sensors, as well as optical image sensors are generally used [1]–[4].

The use of distributed forward scattering radar (FSR) sensors connected via a wireless network can give significant advantages in small and stealth targets detection [5]. Unlike the sensors mentioned above, these sensors may be made in small dimensions, with a light weight and durable assembling. This provides them with the option of a free drop from remotely operated moving platforms, such as unmanned aerial vehicles (UAV). Therefore, they could be more easily deployed on hazardous or remote areas. Moreover, use of radio frequencies not only allows large transmitter-receiver separations (larger than 150m for personnel detection), but also leaves the system unaffected by external factors such as foliage, smoke screening and rain.

The goal of this article is to show the current state of research in the development of a ground-based FSR network for ground target detection and automatic target recognition (ATR), conducted at the University of Birmingham. This research began from the theoretical and experimental study of ATR using the FSR principle [6]–[7]. Later on, the concept of a ground-based FSR for ground targets' detection and recognition was formulated and a study of FSR was performed in terms of wave propagation, targets' characteristics, FSR power budget and data processing algorithms [8]–[11]. A brief mention on future work in the FSR network research and development is made at the end of this article.

System concept

A wireless network of FSR sensors has been designed for situational awareness in ground operations (Figure 1). It detects and recognises ground targets such as personnel and vehicles entering the network coverage area.

There are a number of features distinguishing the proposed system from existing ones, which are listed below.

A. Free drop of sensors

Sensor deployment does not require manual installation. Spreading the sensors from a moving platform such as UAV or ground vehicle is possible. This defines a number of specifications for the system.

First of all, sensors should be compact and shockproof (see Figure 2 for an example), equipped with a special device for smooth landing, such as a special parachute or umbrella.

Dropped sensors are situated directly on the ground surface in random positions in space (earth coordinates). Maximum allowable baseline lengths are in the order of 150–200m for human targets. A unidirectional antenna system is used

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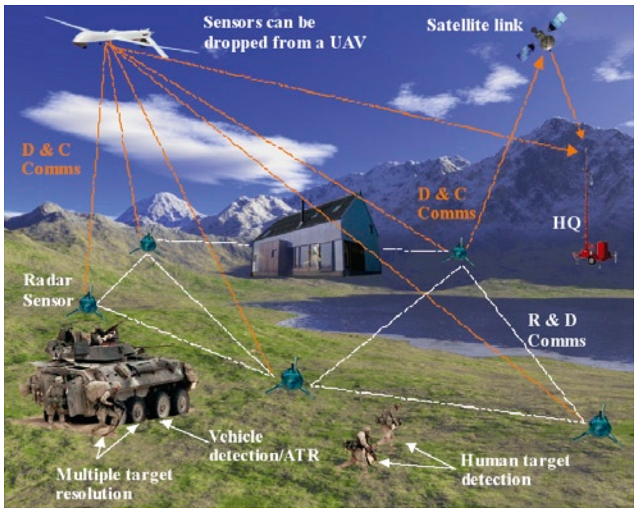

The concept of the FSR micro-sensors radar network (sensors enlarged for visibility).

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Examples of sensors design.

to establish the radar and communication channels with neighbouring nodes placed in unknown directions. Once on the ground, sensors should be able to operate for approximately thirty days on batteries.

For situational awareness, data collected by the sensors should be transferred to headquarters (HQ) in the form of messages, and a wireless link should be established between sensors and HQ directly (assuming the distance from the network to HQ is not too long). Alternatively, messages could be carried using either a UAV network or a Low Earth Orbited Satellite (LEOS), as shown in Figure 1. Except for the data from the sensors to HQ, reverse flow of commands to manage sensor operational modes may be transferred through wireless links, named as D&C Comms (data and control communications) on Figure 1. Additionally, transfer of radar data and control information regarding the sensor operational mode is required between the sensors themselves. This is referred to as R&D Comms (radar and data communications) on Figure 1.

B. The use of the FSR effect tor target detection and recognition

Some system peculiarities follow from the principle of target detection and recognition. The FSR effect gives some advantages in increasing target radar cross sections (RCS) for targets with dimensions bigger than the radar wavelength. It is then possible to decrease the radiated power of the radar transmitter and save battery life. It is also possible to detect stealth targets [5] and operate in all weather and climatic conditions, as well as penetrate smoke and foliage screening.

Perhaps the main question for this system is the choice of operational frequencies for the radar and communication channels. Choosing the system operational frequencies is a result of compromise between many factors. Lower frequencies have less propagation losses (especially for antennas situated directly on the ground [9]), diffract around ground obstacles and penetrate foliage much better. On the other hand, antenna efficiency and target RCS [8] decrease significantly. Moreover, high frequencies are, in theory, desirable for accurate target recognition. We consider now the combined operation of the sensor in two bands:

- A VHF channel is used for target detection and target parameters estimation (such as speed, baseline crossing point, and target dimensions evaluation). This channel is in constant operation.
- A UHF band signal is used for ATR and is switched on in the event of target detection.
- Both VHF and UHF bands may be used for intercommunication between nodes and for data transmission to HQ using the same equipment as for radar channels.

The unified sensor structure can thus be presented as in Figure 3, having a number of antennas for different bands, a navigation (GPS) receiver to retrieve sensors' ground coordinates and two-band transceivers connected through ADC and DAC to the computer (DSP processor). Each radar channel in the FSR configuration operates in continuous wave (CW) mode and has no range resolution. Therefore it is possible to obtain long integration times for target signals and to have a sufficient signal-to-noise ratio (SNR) with very limited radiated power. However, in conjunction with the unidirectional antennas, this means that foliage clutter is picked up from the whole volume illuminated by the sensors. As a result, clutter power, spectrum, as well as its characteristics should be investigated. Results of our research in these areas can be found in [11], but will not be further considered in this article.

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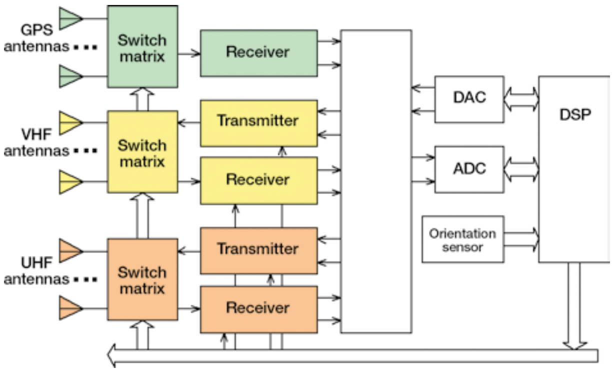

Unified sensor block-diagram.

Signal processing

As mentioned previously, the system is designed for the detection and parameter estimation of ground targets such as personnel and vehicles. In the case of vehicles, automatic target recognition (ATR) is also performed. All these tasks are currently achieved through signal processing at the central post. The inputs to the signal processing are the signals recorded as a target moves across a single transmitter-receiver baseline at the 64 and 434 MHz channels. These signals will be referred to as target signatures hereafter. It has been shown [10] that these signatures resemble the real part of a two-sided chirp signal, shaped in amplitude by propagation losses and target RCS variation during its motion. Prior to the signal processing at the central post, a pre-detection algorithm is executed at the receiving node to retrieve the target signatures.

An overview of the algorithms employed in the system is provided in the sub-sections below.

Pre-detection algorithm

Target signatures are sent to the central post after a pre-detection algorithm is executed at the receiving node. The reason for this is because the radio channel does not have the capacity to transmit all the signals received from the monitored area in real-time. The idea is to continuously detect whether a block of received data contains a part of a target signature at the 64 MHz channel. If it does, this part of data, along with the corresponding 434 MHz data is sent to the central post for further processing. The algorithm is not conclusive as to the presence of a target as it has high probabilities of detection and false alarm. The final decision regarding the presence of a target is made at the central post.

The algorithm itself is based on complex envelope FFT processing (Figure 4). Data are split into blocks using a sliding window. Each block is converted to the frequency domain. The magnitude of spectral components of the signal is compared to a pre-defined threshold.

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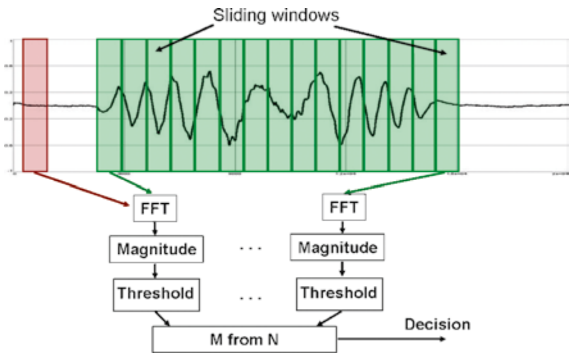

Pre-detection algorithm.

If a spectral component exceeds the threshold, signal data are assumed to be present within the block, which are then sent to the central post sequentially. The outputs from the sliding window are summed to make a decision on the presence of a target. The threshold level is generally set as N times the rms noise level, where N depends on the probability of false alarm. However, in our case there is a strong presence of clutter concentrated within a narrow frequency band [11]. This means that the threshold value should be estimated using FFT samples within the clutter band. For this purpose, a two-step procedure is used. An initial threshold is calculated in the whole band $[0, f_s/2]$, where f_s is the sampling frequency. All samples exceeding this threshold are regarded as clutter. The final threshold is set by considering these samples only. Figure 5 shows an example of data spectra (clutter and noise a) without and b) with target data) plotted against the calculated thresholds (k-sample number).

The simulated parameters are: clutter bandwidth – 0.5 Hz, baseline – 100 m, signal-to-noise ratio – 15 dB, clutter-to-noise ratio – 20 dB, target velocity – 2 m/s. The FFT length is 128 points and the sampling rate is 20 Hz.

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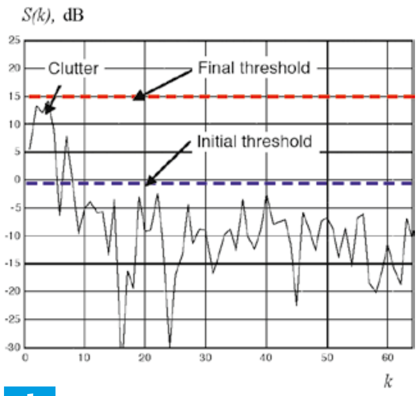

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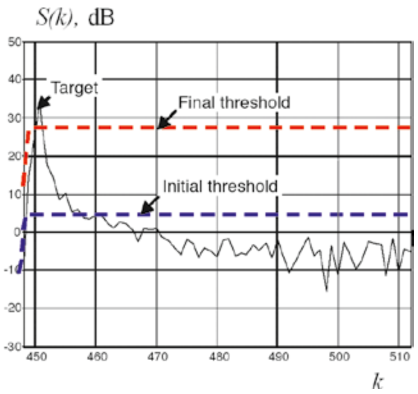

Examples of data spectra, a) without and b) with target data present.

As soon as the target signatures are retrieved, they are sent to the central post. A flow diagram of the signal processing carried out there is shown in Figure 6. Each block is then briefly described.

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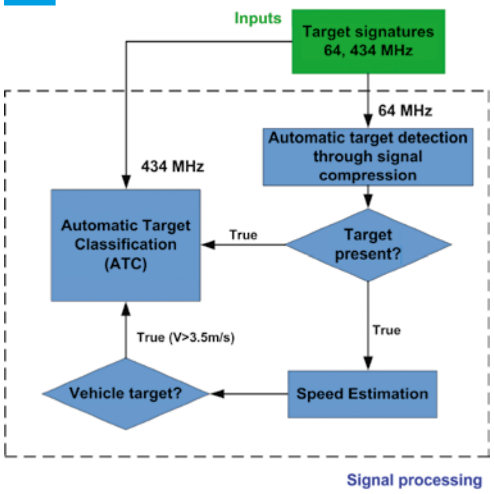

Signal processing flow diagram at the central post.

A. Target detection and parameter estimation

Both target detection and parameter estimation operate with the 64 MHz data. Target detection is achieved through compression of the target signature (matched filtering). The problem in this approach is that the target phase signature depends on the speed of the target. Therefore, the received signal is correlated with a set of reference signals. Each reference signal is the phase signature of a point target moving normal to the baseline with a particular velocity. This process can be thought of as passing the received signal through a bank of filters. The compression output has a maximum at the output of one of the filters, referred to as the matched filter. This maximum is then compared to a threshold level to decide the presence of a target. If a target is indeed present, the velocity used in the matched filter gives an estimate of the target speed. The reader is prompted at [10] for more information on the compression and velocity estimation algorithms. Figure 7 shows the maximum compression output from each filter as a function of the estimated velocity. The target is a human, running across a 80m baseline. The compression output at the matched filter is plotted in Figure 8. The threshold in Figure 8 has been calculated assuming a 10^{-3} probability of false alarm.

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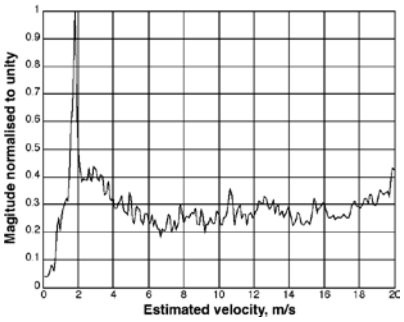

Velocity estimation output.

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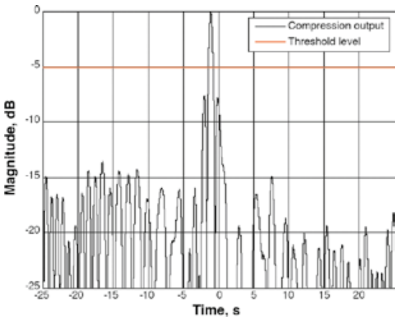

Compression output at the matched filter.

B. Automatic target recognition

On the basis that a target is detected and that it is a vehicle (for the moment it is assumed that targets with speeds greater than 3.5 m/s are vehicles), the 434 MHz target signature along with the estimated speed are passed on to the ATR algorithm. An ATR algorithm for ground FSR has already been developed [7], and it was experimentally proven for target signatures obtained at 869 MHz. The algorithm is based on Principal Components Analysis (PCA). It compares the target signature in the frequency domain with a database of signatures collected for different vehicles to find the closest match.

Due to signal propagation issues, it was required to reduce the operating frequency to 434 MHz. Therefore, it was necessary to test whether the algorithm is functional in this or even lower frequencies.

Figure 9 shows plots of all training data in the principal component space. Training data were signatures collected from three different cars (Volvo V40 – blue squares, Peugeot 406 – red circles and Land Rover Discovery – green triangles), at three different frequencies (64, 151 and 434 MHz). The signatures were collected with the cars moving normal across the midpoint of a 40m baseline. It should be noted that the Peugeot and Volvo are of similar dimensions and shape, while the Land Rover is significantly different than both.

A good separation between different types of cars can be seen in all frequencies. Moreover, 151 MHz seems to provide the best results. This is in contrast to the general impression that the higher the frequency (i.e. 434 MHz in our case), the better the classification. This can be explained by the presence of clutter, which is stronger in the 434 MHz channel than in 64 and 151 MHz. Further, 151 MHz provides better results than 64 MHz because it gives more detailed frequency information regarding the targets' spectra. Based on these results, it may be that a single frequency channel between 120–150 MHz will be used both for detection/parameter estimation and ATR. A modification has also been made to the algorithm in [7]. Target speed estimates are used to equalise the extent of the target signature with that of all signatures in the database. At this stage it should be mentioned that perhaps the PCA is not the best option for ATR [6] and it is possible that a different algorithm will be employed in the future, such as the one described in [12].

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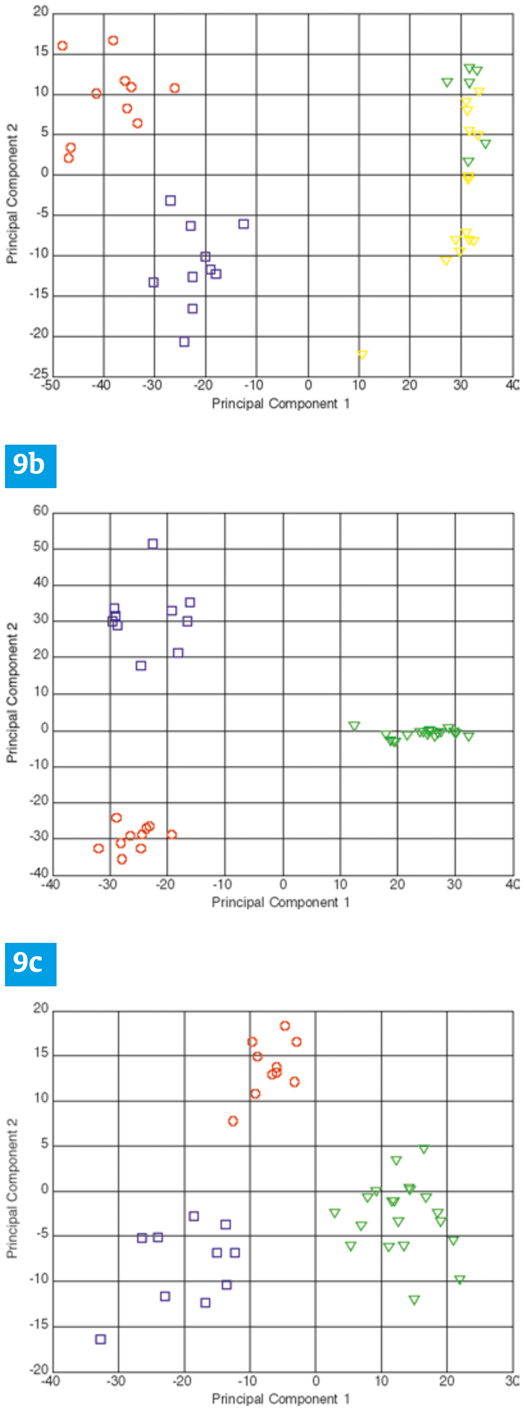

The location of data for each vehicle in the 2-component PCA space (a) 64 MHz, (b) 151 MHz, (c) 434 MHz.

Conclusions and future work

The current stage of research and development of a micro-radar network for situational awareness has been presented in this paper. Due to its principle of operation, it possesses several advantages compared to similar systems, mainly in its deployment methods and its robustness to adverse weather conditions and allowable transmitter-receiver separations. The system can be used for the detection, parameter estimation and classification of ground targets. Even though each signal processing algorithm is independent, all algorithms are interconnected to increase the functionality and accuracy of the system. Our main efforts are now concentrated on the practical realisation of the system and on the development of more advanced (and accurate) ATR algorithms.

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