Target detection in urban scenarios using netted radar multipath signals

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Abstract

In urban environments, multipath and obscuration by buildings decreases the ability of radar systems to detect targets and also increases the number of false alarms caused by image artefacts. To reduce these problems this paper proposes a network of low-cost easily-deployable radar sensors that are set up in a multiple-input multiple-output (MIMO) radar configuration. An analysis is given of the signal processing required to combine the data from several co-operating radar sensors while using building information and including the effects of multipath propagation. The key part of this idea is that the known building positions from a database are used to determine the origin of multipath signals. This process enables the removal of artefacts and allows the sensors to "see around the corner" of buildings.

1. Introduction

The threat of asymmetric warfare makes it increasingly likely that a significant proportion of future military operations will be carried out in the urban environment. An essential military capability is the ability to fight in urban terrain under adverse conditions. As a sensor, radar has the well known advantages of a day or night, all-weather capability. Radar also works in smoky or dusty conditions that might arise during a battle situation. However, obscuration by buildings decreases the ability of radar to detect targets. Also, the radar signal may travel via several paths between the transmitter and receiver due to multiple reflections from buildings. These multipath signals cause artefacts in the data that appear to be targets, which increases the number of false alarms reported by the system. These effects have reduced the operational utility of radar systems in urban environments.

Recently, there has been an increased interest in netted radar and multiple-input multiple-output (MIMO) radar, which use a network of sensors to combat propagation problems. This paper proposes that a network of spatially-distributed low-cost and lightweight radar sensors be used in a MIMO configuration in conjunction with a database of building positions to detect targets. The sensors could be placed by army personnel or dropped from an unmanned airborne vehicle (UAV). Because the sensors are small in size the antennas have an omnidirectional radiation pattern and the timing of signals is used to determine target positions. The database of building positions could be obtained from a commercially available geographical information system (GIS), or generated automatically from either stereoscopic satellite imagery of the area of interest or lidar measurements from an airborne platform. The key part of this idea is that the known building positions are used to determine the origin of multipath signals. In addition to improving line-of-sight target detection, this process also allows the sensors to "see around the corner" of buildings. Naturally, an accurate database of building positions is required as an input to the signal processing algorithms. However, the accuracy need only be of the same order as that required for target location. The greater the number of sensors used, the greater is the ability to accurately locate targets, resolve ambiguities, and suppress clutter.

An illustration of multipath geometry is shown in Figure 1 for a system that uses one transmitter and one receiver to detect two targets. The target on the right has a direct line of sight to both the transmitter and receiver. There are also two possible reflection points on the top building that could result in signals travelling between the transmitter, the target, the building, and the receiver. These reflected signals are the source of false-target artefacts. The target on the left has no line of sight to either the transmitter or the receiver. However, the target could be detected using reflected signals from the building.

The remainder of this paper gives an introduction to the concept of netted radar and how it can be used to detect and locate targets using timing information only. It then goes on to describe how algorithms can be modified to take multipath into account. Finally, an example is given of how multiple targets can be detected in situations where there is no line-of-sight between some of the targets and the sensors.

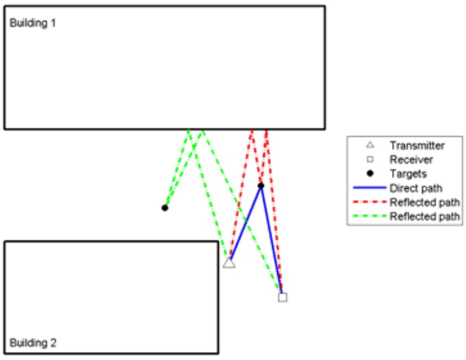

FIGURE 1. Concept diagram for target detection using multipath radar signals

2. Netted radar

Among the radar community there is currently an increased interest in radar systems where there is more than one transmitter (Tx) and receiver (Rx). These are variously referred to as multistatic radar, netted radar, or multiple-input multiple-out (MIMO) radar. Such systems are now feasible due to advances in technology in the fields of communications, electronics, and aerospace. These technologies are required for high-bandwidth wireless and fixed-line transmission, digital signal processing, electronic beam steering, multi-channel antennas, and synchronisation systems such as the global positioning system (GPS) (Papoutsis *et al.*, 2005).

MIMO radar as a concept was independently proposed by Bliss & Forsythe (2003) and Fishler *et al.* (2004) and is inspired by the use of MIMO configurations in communication systems. The main idea behind MIMO radar is the use of statistically independent looks at the scene of interest. There is a wide variety of methods for achieving this independence, such as spatial, frequency, or temporal diversity but it is typically spatial diversity that is associated with this topic. There are many advantages to using a set of spatially spread antennas. The first of these is that more of the energy transmitted by the transmitter is received by the various receivers, which improves the signal-to-noise ratio. The localization of targets is more precise because the point spread function of individual Tx-Rx antenna pairs is oriented differently for each pair and combining the data reduces uncertainty in a target's position. The statistical independence of received data not only aids detection but also target recognition because complex radar targets have different signatures when viewed from different directions and it has previously been shown that the more directions a target is viewed from the better the target recognition performance. In complex environments where obstacles such as trees and buildings can obscure the line-of-sight from a radar antenna to the target, having a greater number of antennas means the target is more likely to be seen by any one of the antennas. Finally, in a battle situation if any single node is eliminated, the system is not completely disabled but merely suffers a reduction in performance. This makes it more resilient to attack.

From a data fusion point of view there are two major ways of combining data. The first of these is to carry out a local detection procedure at each receiver and transmit the detected target time-delay data to a central processor, which combines these detections to give an overall picture of the scene. When the Tx, Rx and targets are coplanar it is well known that a bistatic time delay maps to an ellipse whose foci are located at the Tx and Rx positions and whose size is determined by the delay (Hayward & Lane, 2008). The ellipses for each Tx-Rx pair are calculated and the coordinates where the ellipses intersect are determined. This process is illustrated in Figure 2 for a two-target scenario with two transmitters and two receivers. In an ideal situation all ellipses intersect at true target positions, which is the case in Figure 2, where six pairs of ellipses intersect at target coordinates. In practice, target-related intersections do not perfectly overlap but they do cluster around the true target position. This is illustrated in Figure 3, which shows intersections of the ellipses from Figure 2 that have been modified by adding a small independent random distance in the definition of each ellipse. Two clusters each containing six intersections can clearly be seen. A clustering algorithm would be able to detect these clusters and the target positions can be estimated from the mean of the intersection points.

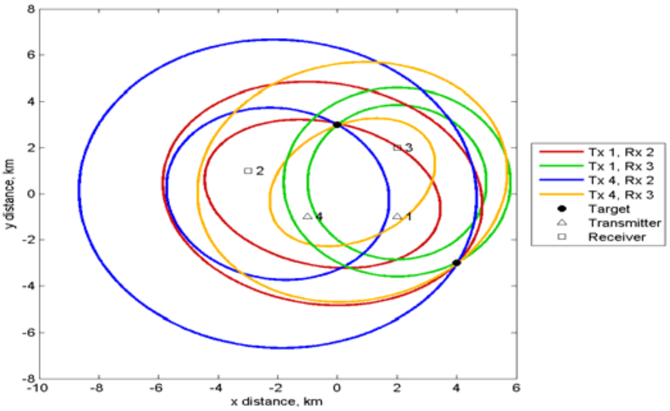

FIGURE 2. Ellipse geometry for a two-target scenario with two transmitters and two receivers

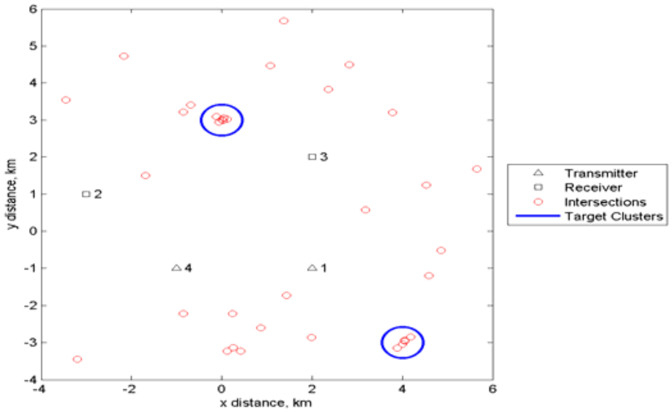

FIGURE 3. Ellipse intersections for a two-target scenario with two transmitters and two receivers

The second method for target detection is for all the receivers to transmit raw radar data to the central processor, which then carries out a centralized detection process. Each Tx-Rx antenna pair generates a bistatic range profile, which is the received signal as a function of time (or distance travelled) after correlation with a reference waveform. When each bistatic range profile is mapped onto the ground plane the resulting 2D map appears as a set of concentric ellipses associated with each of the peaks in the profile. The main target-peaks map to the position of the ellipses in Figure 2. A combined detection map is generated by adding the square magnitude of the individual maps for each Tx-Rx pair. A detection algorithm can then be run on the combined map, which has a high magnitude at target locations. This process has been referred to as incoherent back propagation by Lane & Hayward (2007).

Out of the two detection algorithms described above, the first method is more efficient from a communications and data processing point-of-view since only detected-target time delays are transmitted and used rather than raw data. The disadvantage of this intersection-based algorithm is that information is discarded during the local detection process, which results in a non-optimal overall detection performance. It might be thought that centralized detection should result in increased system performance when compared to an equivalent decentralized process. However, simple centralized processing of the data using incoherent back propagation where several targets are present results in an increased number of false alarms caused by intersections between target signals from different Tx/Rx-pair channels (Doughty, 2008). Therefore more research is required into algorithms that give good detection performance with an acceptable false alarm rate.

One aspect of MIMO radar is the need to separate the different channels defined by each Tx-Rx antenna pair. Although this could be done by using different frequencies for each channel, the overall bandwidth of such a system could be very high if a large number of transmitters were used with each emitting a high-resolution waveform. One way to circumvent this problem is to time-multiplex the pulses transmitted by each receiver. Although this might be a simple solution from a waveform design perspective, the required synchronization would add complexity and each channel would not be recorded at exactly the same time, which would have implications for sensitive systems. An alternative is to transmit pulses at the same time and on the same frequency but to use orthogonal waveforms to separate the channels. An interesting waveform design of this form is based on Golay complementary pairs. In their autocorrelation function each pair has equal and opposite sidelobes that cancel to give zero sidelobes overall. In addition to this, certain sets of pairs have zero cross-correlation, which is ideal for MIMO radar. Non-zero Doppler shifts cause increased sidelobes, so these waveforms are most appropriate for slow moving targets in clutter (Donnet & Longstaff, 2007). Other waveforms should be used when trying to detect faster moving targets.

The practical design of a MIMO radar system has been carried out by Derham *et al.* (2007). This showed that it is possible to build a working system with low-cost components while maintaining a satisfactory target detection performance. Nevertheless, for a high-performance system several technical challenges remain, including time and frequency synchronization of the transceivers, data fusion processing, and managing the high bandwidth communications link. A different radar network architecture for target detection proposed by Cherniakov *et al.* (2008) is based on the forward scattering radar principle. However, such a system is based primarily on targets moving near the baseline between adjacent pairs of transmitters and receivers and does not fully utilise the complete network of sensors.

3. Multipath signals in urban scenarios

In urban environments radar signals are reflected by buildings surfaces and diffracted around building edges. For the purposes of this paper it is assumed that the frequency of the radar system is high enough such that diffraction effects can be neglected but not so high as to allow diffuse reflection. Thus the only modes of radio wave propagation considered here are free-space propagation and specular reflection. The reflection of radar signals from building surfaces has two effects. The first of these is that direct Tx-building-Rx signals in a radar picture are considered to be clutter and have the effect of reducing target detectability for a constant false alarm rate. The second effect is that, when illuminating a target, the radar signal can travel via multiple paths due to reflections from the buildings. Such paths for a single wall and target are Tx-target-Rx, Tx-wall-target-Rx, Tx-target-wall-Rx, and Tx-wall-target-wall-Rx. These are illustrated in Figure 1. The first path results in the direct line-of-sight (LOS) signal that is normally used in radar systems. The next two paths involve first order reflections and the final path is a second order reflection. When using standard radar processing the non-LOS signals appear as artefacts in the data with a delay greater than the true target delay, due to the extra distance travelled. The combination of direct building signals and multipath artefacts makes target detection in urban scenarios a challenging problem.

It is often claimed that MIMO radar is useful in scenarios where multipath transmission is present. A study by Lane & Hayward (2007) showed that spatial MIMO radar can help mitigate the effect of multipath from tree trunks when attempting to detect personnel in wooded areas. This study relied on a change detection process and sufficient attenuation from tree trunks that the LOS signal can be detected. In urban areas, the reflections from buildings are likely to have high magnitudes and should be taken into account directly. To do this it is required to know building positions, which could be obtained from a geographic information system (GIS) database. Such an idea is a subject of current research. Kaya *et al.* (2007) have proposed an emitter location algorithm based on known building positions and properties. The US defence advanced research projects agency (DARPA) is currently funding research into target detection using airborne radar and known multipath reflections to detect non-LOS targets in urban canyons. A statistical analysis of the radar coverage to be expected from such a system is given by Krolik *et al.* (2006) and the feasibility of using multipath radar with Doppler processing to detect moving targets has been examined by Linnehan & Schindler (2009). Here we show how the MIMO radar algorithms described in the previous section can be applied in situations where multipath is present, but without requiring the use of Doppler information.

The multipath MIMO/netted radar algorithm is explained using the specific scenario shown in Figure 4. In this scenario there is one transmitter Tx1, one receiver Rx2 and one target. There is a building in the vicinity of the target that causes multipath signals as outlined above. The direct signal places the target on the inner red ellipse as would happen for a standard bistatic radar configuration. The multipath signal Tx1-target-wall-Rx2 produces a second peak in the received data. If this peak is not specifically attributed to multipath it maps to another ellipse (yellow) with Tx1 and Rx2 as the foci. Similarly, the Tx1-wall-target-Rx2 signal produces the purple ellipse and the Tx1-wall-target-wall-Rx2 signal produces the grey ellipse. The three signals described thus far have not assumed any knowledge about the building. If the position of the reflecting wall is known, the multipath signals can be taken into account using virtual transmitters and receivers. The first of these signals can be calculated by replacing the wall-Rx2 segment of the Tx1-target-wall-Rx2 path with a virtual receiver Rx3. This places the target on the green elliptic arc with Tx1 and Rx3 as foci. Similarly, the accounted-for Tx1-wall-target-Rx2 signal is calculated using a virtual transmitter Tx4 and the real receiver Rx2, resulting in the dark blue ellipse. Finally, the second order reflection path has a virtual transmitter and receiver, and results in the light blue ellipse with Tx4 and Rx3 as foci. Any signals relating to targets within the building boundary can be rejected as it is known that they must be reflection artefacts. In addition to this, reflections from the building itself can be excluded because its position is known. The resulting set of ellipses and elliptic arcs has only one location where the four properly accounted-for ellipses intersect, and that is at the true target position. In a similar manner to the previous section, multiple targets can be detected in practice by looking for tight clusters of intersections with the number of intersection appropriate to the measurement geometry. Alternatively the incoherent back propagation approach described in the previous section could be used with the above multipath logic to generate a detection map that has a peak at the true target position.

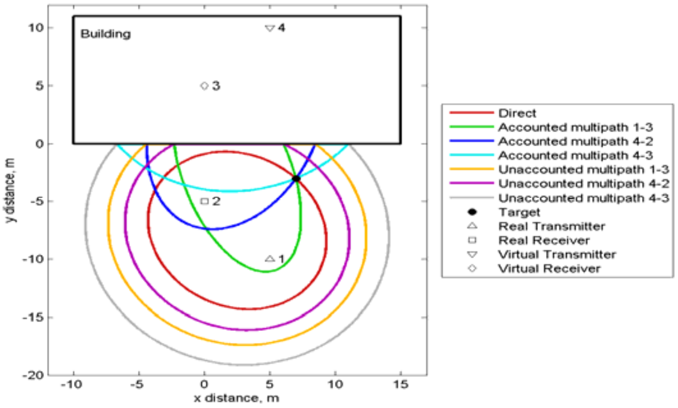

FIGURE 4. Target detection using one transmitter and one receiver, in the presence of multipath caused by a building

4. Non-line-of-sight target detection

The multipath netted radar algorithm described in the previous section can also be applied to the situation where there is no line-of-sight between the target and either the transmitter or receiver (or both). In this case the target would be detected via reflections from the buildings. This mode of non-LOS target detection allows a greater area of the scene to be under surveillance than would be possible using a typical LOS radar system.

An example of how LOS and non-LOS target detection would work simultaneously is given in Figures 5 and 6. Real nodes 1 and 2 each act as both transmitters and receivers, as do the equivalent virtual nodes 3 and 4. One target is located at (15,-7) and has a line of sight to both real nodes. The second target is located at (5,-8) where there is no line of sight to either real node. All the possible ellipse loci associated with direct and multipath signals for each target have been calculated using nodes 1 to 4 in every combination as transmitter and receiver. The first target has 17 ellipses associated with it. Ten of these have the target on their locus and seven are unaccounted-for multipath signals. The second target has 6 ellipses associated with it. Three of these have the target on their locus, with foci pairs Tx3/Rx3, Tx3/Rx4, and Tx4/Rx4. The other three ellipses associated with this target are unaccounted-for multipath signals. Note that Tx/Rx pairs are equivalent if their transmitter and receiver are reversed. For example, Tx3/Rx4 results in the same ellipse as Tx4/Rx3. These overlapping ellipses have not been included in the above counts.

Figure 6 shows intersections of the ellipses apart from those intersections that appear within building boundaries, which can be removed since they do not relate to real targets. The intersections shown with green crosses do not have a line of sight to nodes 1 or 2 even though they are associated with ellipses defined by those nodes as foci. These intersections are clearly invalid as they have no physical basis and can therefore be removed. The remaining intersections shown with red circles are spread out over the scene apart from the two target positions that respectively have clusters of 45 and 3 intersections in their vicinity. The cluster of 45 clearly outnumbers any other cluster of intersections. The cluster of 3 is the only one of that size in the shadow region of nodes 1 and 2. Both clusters can be used to estimate the target positions.

The large number of intersections does create some scope for ambiguity, especially when trying to detect stationary targets. However, moving targets can be tracked over time to mitigate this problem. True target positions move through an image with a large number of consistent intersections associated with them. Groups of intersections would be detected and added to the track list of a tracking system. Non-target intersections also move in a target-like behaviour over the short term but the individual intersections move in different directions. It would rapidly become apparent to a tracker that such groups of intersections do not represent a target. Any spurious tracks could then be deleted from the list leaving only true target tracks.

Another method for reducing ambiguity would be to use Doppler information for moving targets. This scheme would represent potential target positions as hyper-surfaces in a four-dimensional Doppler-location space instead of ellipses in a 2D location-only space. The extra dimensions would give more scope for a difference between intersections associated with targets and spurious intersections. These differences could then be used to reject non-target signals. The details of such a system are beyond the scope of this paper but would be an interesting avenue for further research.

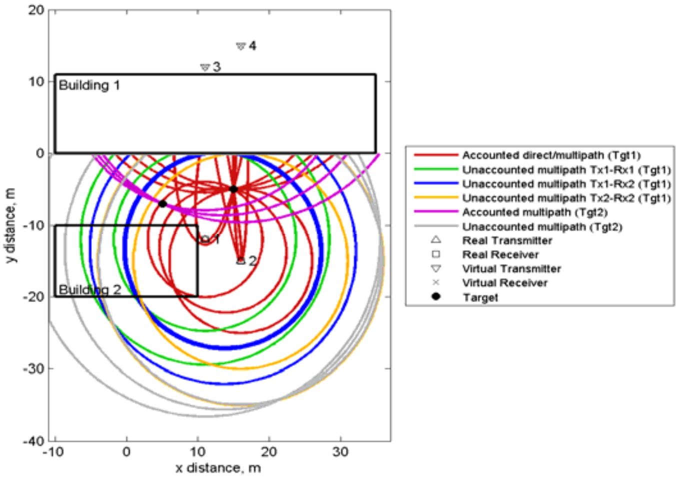

FIGURE 5. Ellipse geometry for two targets in a multipath environment using two Tx/Rx transceivers where there is no line-of-sight between one of the targets and the transceivers.

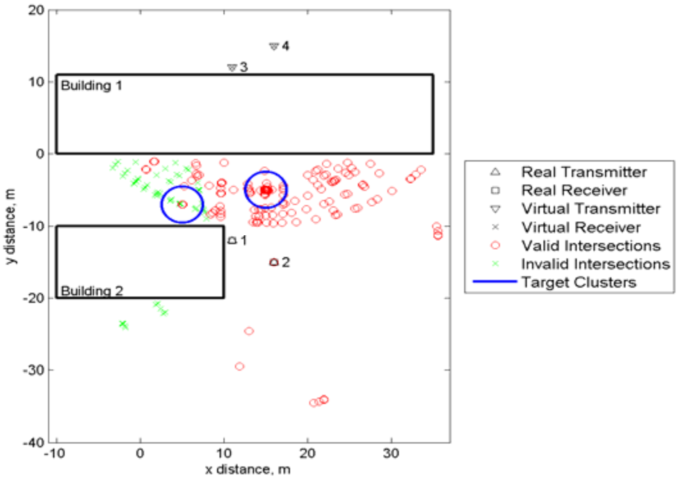

FIGURE 6. The detection of two targets in a multipath environment using two Tx/Rx transceivers where there is no line-of-sight between one of the targets and the transceivers.

5. Conclusions

This paper has shown that a network of omni-directional radar sensors in a MIMO configuration can be used to detect the position of multiple targets using timing information only. In addition to this, if a database of building positions is available, multipath signals in urban environments can be taken into account. This multipath accountability not only increases target detection performance but also allows a network of sensors to detect targets obscured by buildings. Two categories of detection algorithm have been discussed. The first of these uses decentralized detection based on the calculated intersection of ellipses, and has been analyzed in some detail. The second category is a centralized process based on the incoherent back propagation algorithm. More research into the advantages and disadvantages of each type of algorithm is required and it should be determined which should be used in a practical system.

The above analysis has been carried out using simulations only. To determine the practicality of urban target detection it is necessary to test the target detection algorithms using measured data. It is recommended that the collection of such a set of measurements be funded so that the algorithms may be developed to a level where they can be deployed in an operational environment.

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