

Affordable high-performance radar networks for homeland security applications

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Abstract — High-Performance Radar Networks have been deployed for Homeland Security Applications. Having the radars on a network allows for increased coverage via multiple radars, as well as the communication of situational awareness in real time to multiple remote users. The radars and networks exploit commercial-off-the-shelf (COTS) technology to be easily affordable for the wide-area surveillance needed for these applications. Implementing radar networks over the Internet enables the straightforward integration of operational systems. Results from a deployed three-node radar surveillance network covering western Lake Erie are presented. These results include the fusion of target tracks from the three radar nodes.

Index Terms — radar, network, surveillance

1. INTRODUCTION

Homeland Security refers to the goal of detecting and defending against threats to public safety posed by potential attack by hostile individuals or groups. Homeland Security applications for radar differ fundamentally from most military applications. The high price of military radars is justified by the critical and urgent need for protection in combat zones or near high-value assets. Homeland Security, in contrast, deals with threats that materialize infrequently and can occur anywhere. Surveillance to counter such threats must be deployed simultaneously across huge areas on a permanent 24/7 basis. Therefore, low-cost is a fundamental requirement for sensors used for Homeland Security surveillance.

Homeland Security includes such applications as maritime domain awareness, border and law enforcement, critical infrastructure protection, transportation security, port security and coastal surveillance. All of these applications require cost-effective detection and tracking of small, fast, maneuvering targets, often in dense target environments. Targets of interest include small watercraft on lakes, rivers or seas, snowmobiles on snow or ice cover, other vehicles, and even small aircraft.

Practical solutions for these applications must provide continuous, day-or-night, all-weather, wide-area surveillance with automated detection, localization and warnings of threats. A single shore-mounted radar can survey many hundreds of square kilometers of water surface. A network of such radars provides a composite wide-area situational awareness picture. In order to provide automated detection of threats, high-quality target track data are needed from each radar sensor, along with sophisticated criteria to determine suspicious target behavior. Practical solutions must also minimize operator interaction, as system cost includes the human labor needed to operate it.

In [1], low-cost radar surveillance systems for tracking small vessels on water were described. These were single-node systems that were only connected to an external network in order to send out alerts. In this paper, we present a network of several geographically separated radar nodes, radar data servers and operator viewing workstations. A pictorial view of the network concept is shown in Figure 1. Such a network has the advantages of:

- increasing coverage area
- filling in gaps in coverage
- improving detection probability
- providing 24/7 real-time situational awareness to multiple remote users
- providing support for multiple missions from intelligence gathering to interdiction

The network design components that allow these advantages are:

- network connectivity for each radar node
- high-performance signal processing, detection and tracking at each node
- real-time streaming of target data (tracks and detections) over a network to a central radar data server
- enabling user applications to connect to the server and access the target data
- providing each user with rich display and post-processing capability

All of the above are accomplished in real time while maintaining a low per-node cost.

The radar networks capabilities have been confirmed through a number of operational systems and experimental exercises. The radars on these systems are all able to send their track data to remote users, and are controllable remotely. With inexpensive radars, we have demonstrated effective tracking in dense target environments, and the fusion of tracks from up to three radars, thus providing improved accuracy and target continuity.

2. SYSTEM DESIGN, COMPONENTS & FEATURES

2.1 Radar Node

The design and operation of a low-cost, high-performance radar surveillance node was described in detail in [1]. Typical radar nodes are illustrated conceptually in Figure 1. The Radar Sensor/Transceiver (RST) consists of a COTS marine radar with its antenna mounted on a tower or mast. The radar's received video and timing signals are connected to a Digital

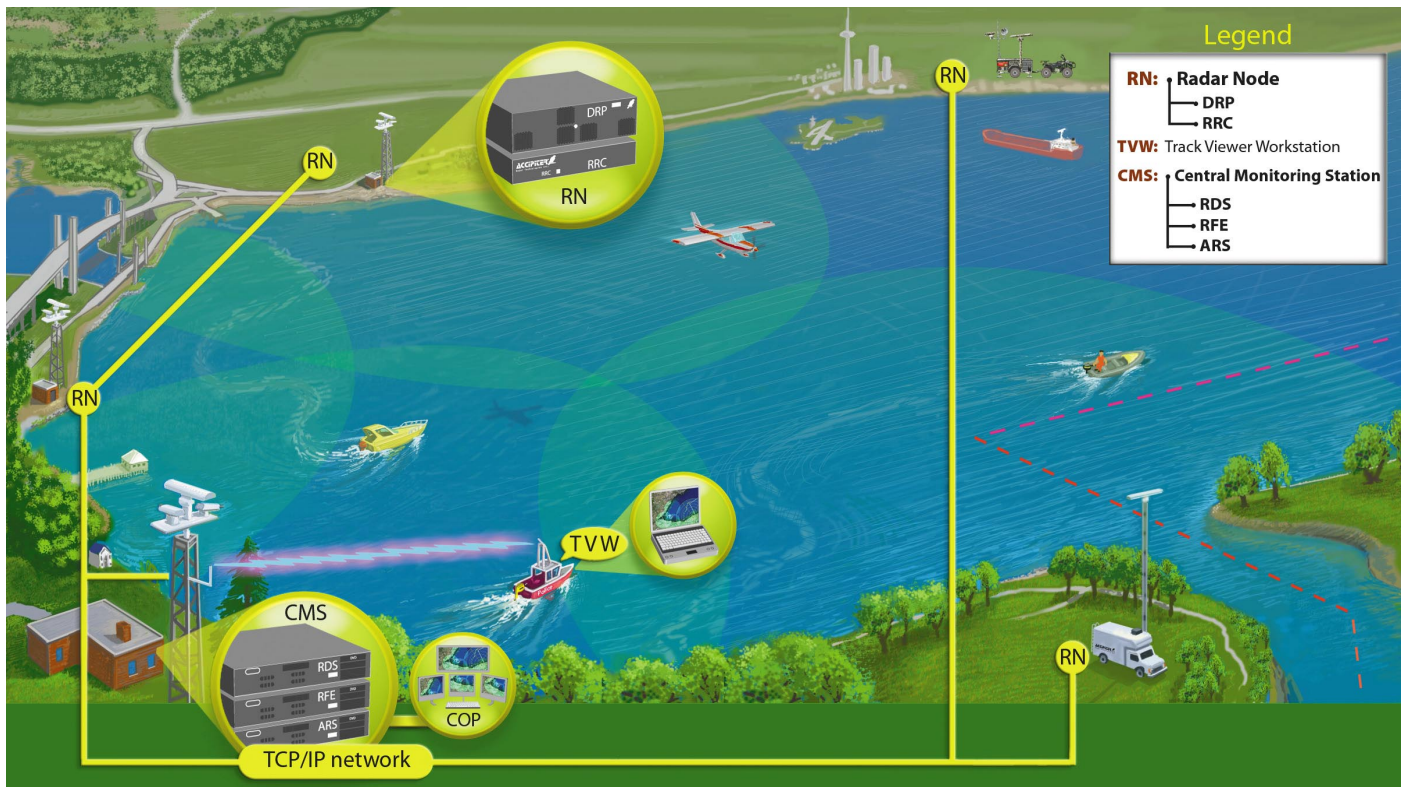


Figure 1: Radar Network Concept

Radar Processor (DRP). The DRP consists of a radar video digitizing card, an off-the-shelf Personal Computer, and specialized digital processing and display software.

The DRP is software-configurable and parameterized; processing includes clutter-map and/or constant false-alarm rate (CFAR) detection, and Multiple-Hypothesis-Testing (MHT) Interactive-Multiple-Model (IMM) tracking. The radar signal processing algorithms can reliably detect and track small, low-radar-cross-section, maneuvering targets in dense target and clutter environments. The DRP also includes user-definable regions where targets are either to be detected or excluded from detection, and interference rejection processing.

To support integration and fusion of multiple radars, as well as to transmit real-time target information to remote users over relatively low-bandwidth networks, real-time target data can be streamed over local-area and wide-area networks, and public networks such as the Internet using standard TCP/IP protocols. The DRP sends its target tracks information to a remote server (the Radar Data Server, described below). Each radar node can thus be viewed as a high-quality surveillance engine, providing a continuous data stream of target track information, with geo-referenced location, speed, heading, ID, date/time stamp, etc.

A Radar Remote Controller (RRC) is associated with each radar node and provides remote operation of the RST sensor hardware. As an Internet Protocol (IP) device, it, coupled with remote access to the DRP, allows the radar network technician to control the radar node from anywhere.

The Automated Radar Scheduler (ARS) is used for unattended, non-continuous or periodic monitoring, or to manage a radar

that is shared by multiple users. It allows scheduling and configuring of radar surveillance events in advance; and it talks to the DRP and RST under program-control to carry out the requested surveillance tasks. The ARS can be carried out at the node level, or across the entire network.

Mobile nodes can also be dropped into the network to fill in gaps or improve surveillance when needed for special events.

2.2 Radar Network

Radar networks (e.g. see TCP/IP network shown in Figure 1) are formed to provide wide-area coverage and/or to provide information to users remote from the radar sensors.

The components of a radar surveillance network are shown in Figure 1. These include one or more radar nodes, each covering a different region, possibly with overlap in coverage. A central Radar Data Server (RDS) collects highly processed target information from the radar nodes and distributes it to a number of remote users who use TrackViewer Workstations (TVWs) (or other applications) to display or post-process target information in real-time. In addition, the radar network technician can administer (i.e. control, schedule and maintain) the entire system using an Administrator's Workstation, probably located at the Central Monitoring Station (CMS), where track information from multiple radars are combined onto a common operating picture (COP).

Such a network allows information from multiple remote sensors to be centralized, integrated and fused. Unlike more dedicated (and expensive) military systems [2], this design uses open COTS network technology and protocols (TCP/IP,

HTTPS, Web Services, etc.) to affordably configure arbitrary secure networks. Internet and wireless network links can be used wherever needed for affordability and flexibility.

Radar Data Server (RDS)

The RDS provides connectivity between the radar sensors and the remote users of the target information. The RDS allows complete target information to be streamed to it from any networked radar location. The target tracks information is immediately stored for subsequent real-time or historical access. All data are stored efficiently in a robust industry-standard Structured Query Language (SQL) database (the Track Database) which is at the heart of the RDS. Multiple users are allowed to access the data in parallel, according to their specific requirements, for real-time viewing and analysis. Specific portions of the integrated target information are distributed to the remote users. Different users have different needs and privileges, and thus are given appropriate portions of the data. Users connect to the RDS using client applications such as the TVWs, Google Earth™ displays, Web services, etc.

Tracks are uniquely time-stamped and maintained in the RDS so that they can be archived indefinitely as well as distributed in real-time. The target information is low-bandwidth, and thus is easily distributed. Tracks are also geo-located in real-time so that target coordinates are readily available for straightforward integration into third party systems (e.g. COPs) or for use with other devices (e.g. cameras). Target locations are provided in both local radar (range, azimuth) and geographic (latitude, longitude) coordinates. Archived track data can be played back and re-processed at rates many times faster than real-time. This allows archives to be used for analysis, intelligence gathering and prosecution. The richness of the target data stream will even support real-time re-processing of the radar data optimized for other missions.

Track Viewer Workstation (TVW)

The TVW provides remote real-time viewing, analysis and alerting. There can be an arbitrary number of TVWs on the network, giving access to multiple personnel. The TVW software has extensive user-customizable features, providing view and functionality according to each user's mission objectives. Features include arbitrary zone specifications, and programmable alarms which automatically trigger events when user-specified target behavior occurs.

Users can overlay real-time tracks (with ID, speed, heading and other info) onto a display with a map or an aerial photograph underlain. The TVW thus effectively becomes a real-time Geographic Information System (GIS). Users can then show track histories, use the cursor to get locations of specific targets, measure distance and angles etc. This makes the TVW tool ideal for patrolling officers on water (or shore), who can get real-time updates on activity in their vicinity (see Figure 1).

Since track information is never deleted but permanently archived for later access, TVWs can be used to generate statistical traffic patterns and maps, and to replay activity for prosecution, training, or research purposes.

A TVW can be set up to perform unattended monitoring, with automatic threat detection and alerting to remote users via e-mail, text messaging, etc. Each user can create his own rules for identifying threats, including perimeter breaches, rendezvous, loitering, speed limits, border crossings, convergence of tracks, etc. A TVW can also double as a remote Administrators Workstation if appropriately configured.

Central Monitoring Station (CMS)

Installations that have multiple radars covering an extended region will typically have a CMS at their Operations Centre. At the CMS, track data from the different radars are integrated and displayed on a COP. A Radar Fusion Engine (RFE) can provide enhanced situational awareness by fusing tracks in regions of overlapping coverage. This is achieved by accessing track tables in the RDS and then updating a master track table in the RDS that results from the fusion process. TVWs and other client applications can access a particular radar track table, or the master track table, as authorized. The fused track data can also be integrated into third-party Command and Control (C2) and Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) systems.

Coverage limitations for any particular node include range attenuation, line-of-sight horizon, and shadows from near-in obstacles. Having several spatially separated sensors allows the coverage gaps to be filled. By fusing the tracks from the various nodes, overall probability of detection is improved. Track continuity is also improved when targets move across the coverage zones.

Network Configuration & Security

Radar nodes are connected to a wide-area network (WAN) or Internet using a firewall and router. Each DRP independently connects to and then sends radar data continuously and in real-time to the RDS. The server receives data from multiple nodes simultaneously and enters all data into the common track database. All connections to the database over the Internet or an unsecured network use secure sockets layer (SSL) encryption. Client certificates can also be used to further restrict connections only to pre-validated users. For sensitive deployments, routers may be equipped with Federal Information Processing Standard (FIPS) 140-2 encryption modules to secure all network traffic.

Asynchronous messaging within the RDS database notifies each client when a new scan of radar track data is available inside the database. This allows each client to be made aware immediately that there is a new scan's worth of data ready to be pulled. Any interested CMS, RFE or TVW can then immediately access the latest data in real time. This also includes web client applications such as Google Earth™, providing visualization of live track data from all DRPs. External access to web services may also be restricted by SSL encryption and passwords on the web server.

At any time, other users (with permission) can access historical data stored in the track database via client applications without

compromising the real-time performance. Web client applications are customizable using hypertext preprocessor (PHP) scripting within the web server, and users can easily develop their own services.

3. TEST OF RADAR NETWORK

An Accipiter radar surveillance network was tested on the western end of Lake Erie in an area where islands obscure coverage. Three nodes were deployed, each including a 25 kW, X-band, marine radar with a 6' array antenna, a DRP and a RRC, and a network connection to the RDS. One of the nodes is shown in Figure 2. Their locations are shown on Figure 3, which is a real-time Google Earth™ screen capture of instantaneous activity on the lake during the summer of 2007. Tracks from all three nodes are present, color-coded for each radar. Figure 4 shows a statistical traffic map for a typical day, generated by a TVW connected to one of the radars.

The radar network was tested during the busy summer months where a large number of targets (pleasure craft, fishing boats, ferries, freighters, etc.) were tracked. Targets in overlapped areas were often tracked by two or even all three of the radars. Radar tracks were streamed to the RDS and subsequently analyzed by the authors in support of testing a radar fusion engine (RFE) currently under development. Preliminary results are encouraging, and clearly demonstrate the feasibility of achieving good fusion performance, even though inexpensive, COTS marine radars were used for the RSTs in the radar network under test.

3.1 Fusion for a real radar network

There are many logistical issues in implementing fusion with a low-cost network of radars. The first is the proper registration of the data, which also includes appropriate calibration of the radars. Our preferred method is on-line calibration, whereby radars are aligned via returns from either a known target position or a strong moving target. As seen in Figure 5, spatial alignment was achieved to a visually acceptable level of accuracy for the three radar nodes, demonstrating feasibility.

The RFE employs track-based fusion, which obviates the need for complex transformations of the data, as tracking is performed in a Cartesian reference plane. Track data registration then simply involves a linear translation of the states under an assumed flat Earth, or a local projection onto a plane for targets at distances where the flat-Earth assumption can adversely affect performance.

The other major issue with data alignment occurs because typical marine radar scan rates are slow (over 2 seconds), and the nodes are not synchronized in their scanning. This means that a target can move a substantial distance between detection by each of the radar nodes. Our approach to address this issue uses a local state prediction to align all tracks onto a common time-base. The (common) times are arbitrarily determined by the next available scan of data from any radar that is part of the fusion activity. This data-driven approach helps make the fusion system robust against data drop-outs and radars going off-line.

Fusion can be successfully applied to these low-cost radar networks because of the advanced tracking algorithms used to produce the tracks themselves. With rich and accurate dynamical information, the association problem is less prone to bad assignments, as full use is made of the velocity and turn-rate state values. The RFE used herein applies a simple best-track algorithm for the final fusion step, but more advanced fusion techniques under development will be seamlessly inserted into the processing chain in the near future.

The final three figures show the vessel tracking example from Figure 5 after the radar node data has been fused via the current RFE. Figure 6 shows the final fused result, which provides a less cluttered display, while still maintaining track integrity. Although not visible in the figure, at some time instances, not all tracks are associated due to registration errors.

Figures 7 and 8 have zoomed in on two regions (Example 1 and Example 2) from Figure 6 to let us examine the fusion results more closely. Figure 7 provides a more detailed look at the best track algorithm in action for Example 1. A single fused track results from the three radar node tracks which are present throughout this interval. The fused track follows Node 2 initially and then switches to Node 1. The performance in this region is encouraging demonstrating duplicate track elimination. Figure 8 presents a slightly different situation (Example 2), illustrating how the algorithm deals with track breaks due to blockage or blind regions when the targets are maneuvering. Time advances from left to right in Figure 8. Initially, the fused track follows the Node 2 track; however, mid-way through the maneuver, the Node 2 track is dropped (a blind zone). The fusion algorithm switches to the Node 1 track to maintain continuity. When the lower variance Node 2 track is reestablished a little later, the fused track switches back to it. Naturally, choice of a different fusion algorithm would help to smooth any such track switches, but nonetheless, the simple best-track algorithm has provided a single track path through this region. Despite registration challenges, Figures 7 and 8 show that sufficient alignment is achievable to make fusion feasible. Considering that the nominal range resolution for these operating conditions was 120 m using non-synchronized, inexpensive radars, this result demonstrates the feasibility of affordable, wide-area radar networks and motivates further development.

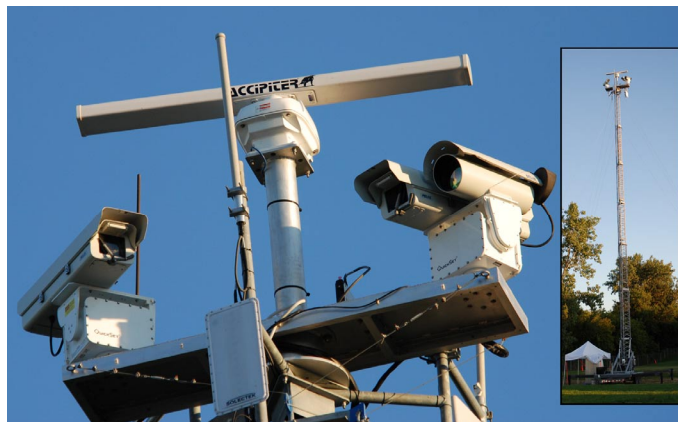


Figure 2: Radar Node: RST on 90 foot tower

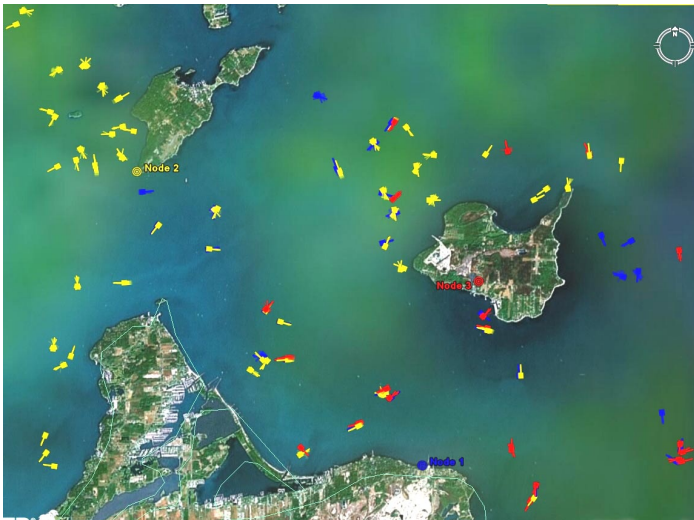


Figure 3: Real simultaneous radar tracks from three nodes (blue, yellow, red)

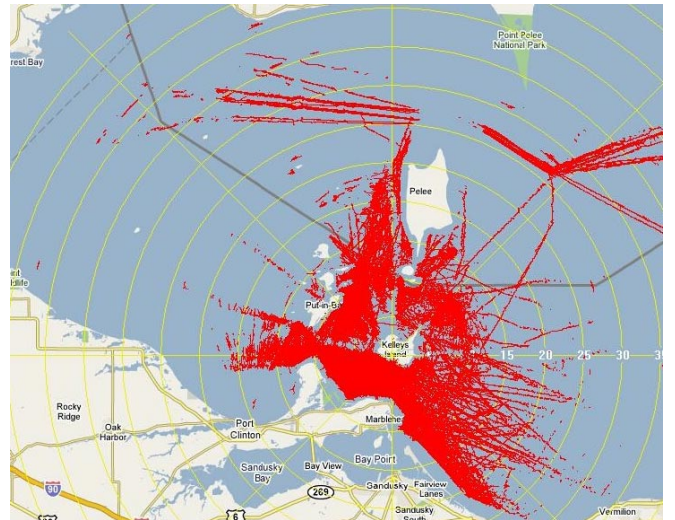


Figure 4: Statistical traffic map on Lake Erie

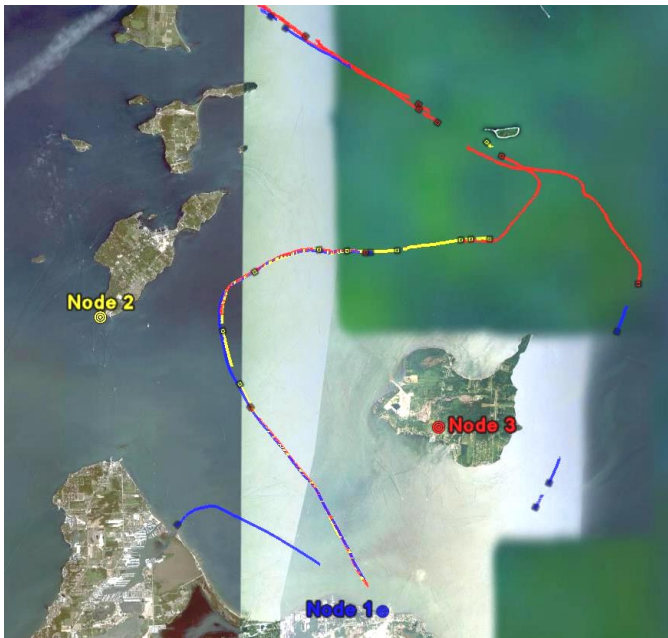


Figure 5: Vessel voyage: radar node tracks (blue, yellow, red)

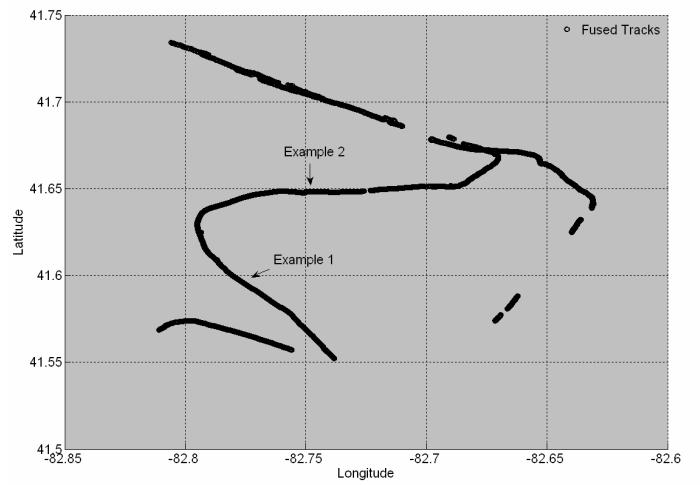


Figure 6: Vessel voyage: fused tracks

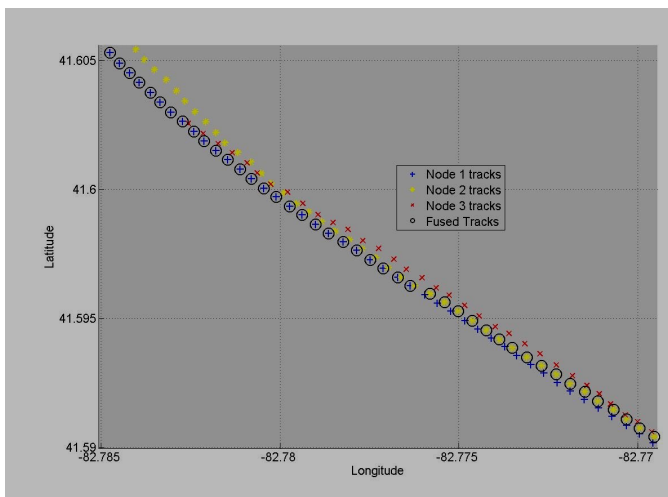


Figure 7: Zoomed Example 1 region showing best fused track

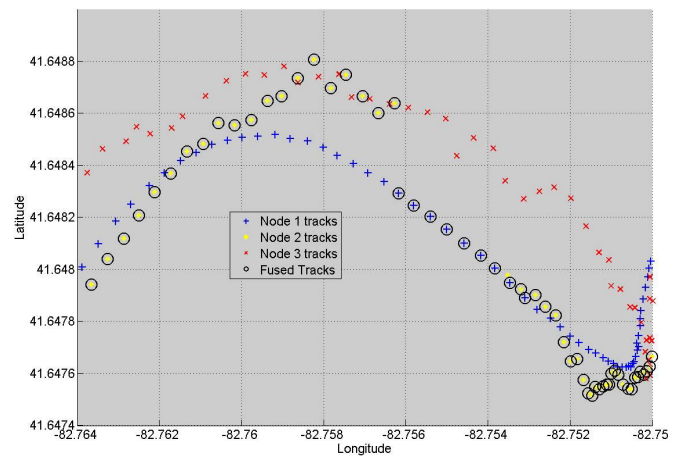


Figure 8: Zoomed Example 2 region showing fused track continuity

4 DISCUSSION

4.1 System Benefits

The radar networks for homeland security applications described herein provide affordable wide-area surveillance. They generate remote situational awareness pictures available to enforcement officers (on land or water or in the air). They allow unattended monitoring of critical areas and real-time alerting of threats to authorities. Having these networks can reduce manpower requirements, and serve as a force multiplier. This makes these systems ideal for border enforcement and critical infrastructure protection.

The radar networks are low cost in procurement, deployment, operation and life cycle. They can thus be affordably and efficiently deployed over wide areas. The radars are somewhat covert, in that they are small and difficult to see beyond a kilometer or so, and that their transmissions are exactly like any other marine radar.

Affordable wide-area surveillance radar solutions (combining the best of COTS and specialized, military-like processing) are now proven and ready for deployments. As more of these networks are deployed, the systems will evolve based on feedback from users. As confidence in their performance increases, information from these sensors will be moved to higher levels of decision-making and command. Having more of these networks out there will ultimately lead to enhanced global security.

4.2 Other Applications

A beneficial application for radar networks is the search and rescue of lost vessels, or those in distress. The archiving of the track data is particularly useful here, since vessel voyages can be traced in time from either their origin or last contact.

Radar networks have many benefits for avian applications [3]. Having several avian radars on an airfield allows more complete coverage. More extended networks provide regional or national bird advisory capabilities [4].

4.3 What Next?

In applications such as coastal surveillance, longer-range coverage than achievable with land-based towers may be needed. In these applications, the radar node could be a payload on a tethered Aerostat, or a low-cost, low-altitude UAV. The bandwidth-efficient network architecture of the radar networks described herein means that SATCOM links using commercial satellites can provide the required connectivity.

The integration of radar data with other data sources is an important part of the design of future CMSs. Better fusion algorithms allow all intelligence to be displayed on a common operating picture. These algorithms are being designed and evaluated. Data sources include other real-time sensors (cameras, acoustics, etc.) as well as historical and empirical

information. AIS and cameras have already been integrated in some deployments.

One of the remaining challenges in surveillance system design is identifying what kind of target a particular radar track really is. Classification rules need to be created that use all of the available information from each track (e.g. target dynamics, height, RCS, history, etc.). The development of such rules requires further experimentation and research. The networked radars presented herein are well suited for such research, since they provide ready access to vast quantities of archived track data. The goal for classification need not be precise target identification (e.g. aircraft model), but instead a more general assessment of danger or recognition of threats.

For security applications, these types of radars are not limited to detecting marine targets. They can also track aircraft and land-based vehicles. Affordable, 3D radars are also under development, where a height-discriminating antenna (multi-beam) system with the appropriate processing will provide altitude information for all tracked targets. Such systems are needed for bird aircraft strike hazard (BASH) management applications, as well as for homeland security applications where distinguishing low-flying aircraft from ground targets are of particular interest.

Finally, cognitive radar networks [5] are also in the early R&D stages. Adding cognition to a radar network will allow the network to automatically adapt to an increased threat level. For example, if a possible threat was detected in a certain area of coverage, the system resources could be automatically optimized by a cognition engine. This would provide improved performance in the priority area, while ensuring system constraints (such as computational resources or network bandwidth) are not violated. The improvement could be achieved by lowering detection thresholds, changing the radar waveform or processing algorithms, or changing the antenna scan rate, for example. Constraints could be managed by dropping a radar temporarily, or restricting other areas of processing.

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